AD-A032 014 AERONUTRONIC FORD CORP WILLOW GROVE PA RADIO TRANSMI--ETC F/G 17/2
MICROWAVE DATA TRANSMISSION TEST PROGRAM DIGITAL APPLIQUE UNIT.(U)
AUG 76 F A JESSEN, N G JONES, J W LAYER F30602-73-C-0203
UNCLASSIFIED RADC-TR-76-268 NL

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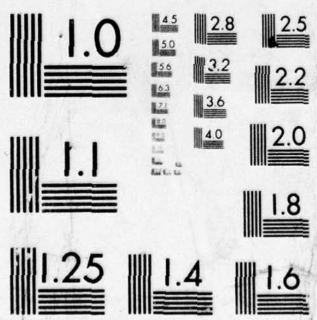

MICROCOPY RESOLUTION TEST CHART
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RADC-TR-76-268
Final Technical Report
August 1976

MICROWAVE DATA TRANSMISSION TEST PROGRAM
DIGITAL APPLIQUE UNIT

Aeronutronic Ford Corporation
Radio Transmission Equipment Engineering Laboratory

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

This report has been reviewed by the RADC Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public including foreign nations.

A previous report, RADC-TR-74-319 (AD#A005686), dated December 1974 described the initial results achieved under this contract.

This report has been reviewed and is approved for publication.

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: RADC-TR-76-268
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): MICROWAVE DATA TRANSMISSION TEST PROGRAM DIGITAL APPLIQUE UNIT.
5. TYPE OF REPORT & PERIOD COVERED: Final Technical Report. April 1975 - December 1975
6. PERFORMING ORG. REPORT NUMBER: N/A Apr-Dec 75
7. AUTHOR(s):
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8. CONTRACT OR GRANT NUMBER(s): F30602-73-C-0203
9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Aeronutronic Ford Corporation
3900 Welsh Road
Willow Grove PA 19090
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: R17200001
11. CONTROLLING OFFICE NAME AND ADDRESS: Rome Air Development Center (DCLD), Griffiss Air Force Base NY 13441
12. REPORT DATE: August 1976
13. NUMBER OF PAGES: 252 (237p.)
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report): Same
18. SUPPLEMENTARY NOTES: RADC Project Engineer: Brian M. Hendrickson (DCLD)
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
Microwave Digital Data Transmission
Digital Modem
Quaternary Baseband
Time Division Multiplex
Telecommunications

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The object of the Microwave Data Transmission Test Program - Digital Applique Unit (DAU) was to design, construct and system test a Digital Applique Unit. The DAU is a time division multiplex/modem equipment which permits conventional FDM/FM microwave radio equipments to be converted to all digital transmission. The DAU is designed to accept and deliver one or two mission bit streams (MBS) with rates up to 12.672 Mbps and a single service channel bit stream (SCBS) of 192 Kbps, and provide an error rate of 10^{-7} for a carrier to noise ratio of 24
10 to the minus 7th power
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db or less with a packing density of 2 bits/Hz. A uniquely designed receiver switch module of the DAU permits the attainment of relatively high diversity gain without the introduction of switch-induced errors or loss of bit count integrity. Provisions for both on-line and off-line BER measurements are provided as part of the built in performance assessment capability.

EVALUATION

The projected conversion of the Defense Communications System (DCS) from a predominantly analog system to a predominantly digital system has created the need for more efficient utilization of frequency spectrum. This is a direct result of the more demanding spectral requirements imposed by digital signals.

The conversion of the DCS to digital can be accomplished by several means, most notably by direct replacement of existing analog radios by digital radios or by the modification of existing analog radios to accept digital information. The latter is most cost effective when the existing analog radios are well within their useful life.

The Digital Applique Unit (DAU) was developed to meet the requirements imposed when converting analog radios to accept digital information. The DAU is designed to require minimal radio modifications in that all essential conversions are provided by the DAU itself.

The performance requirements of the digital DCS provided a formidable challenge in the DAU development in that the existing radios had been designed for exclusively analog use. However the attention paid to design during the DAU development has met that challenge. Radios operating with the DAU will perform very closely to the digital radios soon to be developed for the future DCS. The DAU has therefore provided a positive cost-effective solution for digital conversion of those existing analog radios well within

their useful life in the DCS.

BRIAN M. HENDRICKSON
Project Engineer

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SECTION 1

GENERAL DISCUSSION

1.1 INTRODUCTION

This report has been prepared for the purpose of summarizing the technical activities conducted and the accomplishments achieved by the Radio Transmission Equipment Engineering Laboratory of the Aeronutronic Ford Corporation on a program entitled, "Digital Applique Unit Development". The program which was sponsored and managed by the Rome Air Development Center is a continuation of the Baseband Modem Development program. The effort described in this report covers the period from 1 April through 15 December 1975.

1.2 OBJECTIVES

The basic objective of the program was the development of an applique type equipment which, when operated in conjunction with a conventional FM microwave radio set, will permit the efficient conveyance of digital data and digital service channel signals. The criteria of efficiency of interest was the maximum utilization of the received signal level required to achieve a given bit error rate performance. Specifically, the Digital Applique Unit (DAU) was required to provide a bit packing density of 2 Bps per Hertz and a bit error rate of 1×10^{-7} with a signal-to-noise ratio of 27 dB when used with a standard military remodulating LOS microwave radio, where the noise, signal power and spectral occupancy are defined in a 99 percent RF bandwidth.

The Digital Applique Unit was also required to synchronously time division multiplex a single 192 Kbps orderwire input signal with one or two nominal 12.6 Mbps mission bit stream (MBS) input. The final transmission rate for one or two mission bit stream operating modes was specified to be nominally 13.2 Mbps and 26.4 Mbps, respectively. The MBS input rate requirement was subsequently changed at the request of the sponsoring agency to require satisfactory DAU operation for one or two MBS inputs, each of which may vary at a rate of 3.168 Mbps, 6.336 Mbps, 9.504 Mbps or 12.672 Mbps. The modified MBS input rate specification yields a total of six allowable total MBS input rates; i.e., 3.168 Mbps, 6.336 Mbps, 9.504 Mbps, 12.672 Mbps, 19.008 Mbps and 25.344 Mbps.

Another relevant objective of the program is that the DAU must be capable of providing a satisfactory level of performance when interfaced at baseband with a wide variety of analog type microwave radio sets. As a minimum, the DAU should be capable of being operated effectively with such commonly used radio sets as the Collins-DCS Standard Radio(s), the Motorola AN/FRC 80 and the Aeronutronic Ford LC-8/4 series of equipments. It is, however, imperative that the modifications required of the radio sets, in order to effect a satisfactory interface, be minimal. Preferably, the scope of the radio set modifications should be limited to such things as the by-passing of those baseband circuits which are not essential to the transmission of digital data.

It is further required that the modem portion of the DAU be a dual configuration; i.e., on-line/hot standby transmitter and diversity receiver. In addition, the diversity is to be of the baseband switching type with the selection of the received data from one of the two operating channels being determined by the comparative operational status, AGC voltage level and signal quality of the respective channels. The operational status input to the diversity switch embodies such things as circuit failures, loss of data activity, power supply failures, etc. The signal quality input to the diversity characterizes the dynamic assessment of specific parameters of the received data signal; i.e., relative eye pattern closure, out-of-band noise level, etc.

It was also an objective of the program that the DAU be capable of operating satisfactorily with any one of three possible sources of transmitter timing. The primary timing mode was to be the internal mode in which all timing signals used in the transmitter section of the DAU and in interfacing data sources are derived from an internally located master clock. As an option, the DAU should operate satisfactorily when transmitter timing is derived from an external source. The external source could be either a station clock which varies at the MBS rate or the timing associated with the MBS input. In the former case, timing for the source of the MBS input is supplied by the DAU.

1.3 SCOPE

The subject program consisted of five basic tasks with the completion of each task corresponding to the attainment of a specific goal. The tasks were designated as follows:

Task I	Analysis
Task II	Design
Task III	Implementation
Task IV	Laboratory Tests
Task V	Field Tests

A brief description of the scope and nature of the tasks is presented in the ensuing paragraphs.

As the title designation implies, Task I was primarily devoted to the analysis and evaluation of the applicable specifications and a determination of their impact on the design of the DAU. It encompassed an examination of the modulation, error rate performance, spectral occupancy, sync acquisition time requirements among others. One facet of the analysis effort was also devoted to a determination of the modification requirements of several of the nomenclatured radio equipments with which the DAU is required to operate. The output of this effort was basically a definition of the parameters of the DAU and the formulation of a system block diagram.

The translation of the system block diagram into detailed circuit designs constituted the scope of the Task II effort. It involved the apportionment of the system circuits into functional modules, the formulation of paper designs of each of the functional modules and the generation of interconnecting wiring diagrams. Implicit to this effort was the establishment of a fault and signal monitoring arrangement and the design of circuits and networks which would provide this monitoring function in the system. In addition, the front panel switching, controls and display requirements were established.

Task III of the program involved the generation of circuit board layouts, the fabrication of the circuit board and the subsequent assembly of the DAU equipment. Due to the modification of MBS input rate specification, the implementation of the DAU equipment was actually effected in three phases. During the first phase a redundant modem configuration, which operated with a data input rate of 13.056 Mbps and 26.112 Mbps was completed and shipped to RADC during the first week of October for field evaluation purposes. The implementation of the multiplexer portion of the DAU, which was redesigned to reflect the input MBS rate specification modification, constituted the second phase of the effort. This phase of the Task III effort was conducted while the field test of the modem was in progress and was completed shortly thereafter. The third and last phase of the effort involved the retrofitting of the modem, by the employment of replacement modules in order to permit the modem to operate at the transmission rates which resulted from the input MBS rate modification. This last phase was completed by the third week of November.

The laboratory testing of the DAU equipment, which constituted Task IV of the program effort, was conducted in a manner that was commensurate with the three phase implementation effort described above. The 13.056 Mbps and 26.112 Mbps dual modem model was comprehensively tested in the laboratory in accordance with the applicable acceptance test procedures

prior to its shipment to RADC for field evaluation testing. Preliminary system testing was conducted on the redesigned multiplexer immediately after completion of the implementation phase of the multiplexer development. After completion of the retrofitting effort on the modem, the DAU was subjected to detailed testing in the laboratory in accordance with the applicable DAU Acceptance Tests procedures.

The DAU equipment was delivered on 1 December 1975 to RADC for field testing. The purpose of these tests was to determine if the level of performance achievable with the DAU in an actual operating link satisfied the program objectives. These objectives were presented and discussed in the preceding paragraph. Primarily the field test provided a measure of the error rate performance of the DAU/FM radio set combination under actual operating conditions. It also provided some insight into the effectiveness of the selection diversity technique employed in the DAU under simulated and actual signal fading conditions.

1.4 ACCOMPLISHMENTS

The DAU equipment developed for this program is considered to be totally responsive to the applicable statement of work and its associated amendments. Each and every requirement delineated in the statement of work was met or exceeded by the DAU. It can, therefore, be stated that the need for an applique unit to permit digital data and digital orderwire signals to be efficiently transmitted over analog microwave radios can be unquestionably fulfilled by the DAU equipment developed under this program.

The equipment was implemented as an assembly of plug-in functional modules and packaged in four enclosures; a redundant transmit modem, a dual diversity receive modem, a single time division multiplexer and a single time division demultiplexer. Each enclosure is 8-3/4 inches high, 19 inches wide and 19 inches deep. The weight of each enclosure is less than 55 pounds. A photograph of the DAU is shown in Figure 1.

The redundant transmit modem, which is assembled as an on-line/hot standby, is comprised of a transmitter switch module, two data input modules, two transmitter clock modules, two baseband modulator modules and an associated power supply. The transmit modem serves to transform the serial binary signal exiting from the multiplexer to a four level amplitude waveform. The four level amplitude waveform generated in the on-line unit provides a baseband excitation signal for both units of a redundant FM microwave radio transmitter configuration. The transmitter switch is designed to select the four level amplitude waveform generated in the hot-standby modem as the excitation signal in the event of a failure in the on-line unit. Loss of supply voltage, loss of modulator output, loss of data activity and loss of phase lock are manifestations of a modem failure.

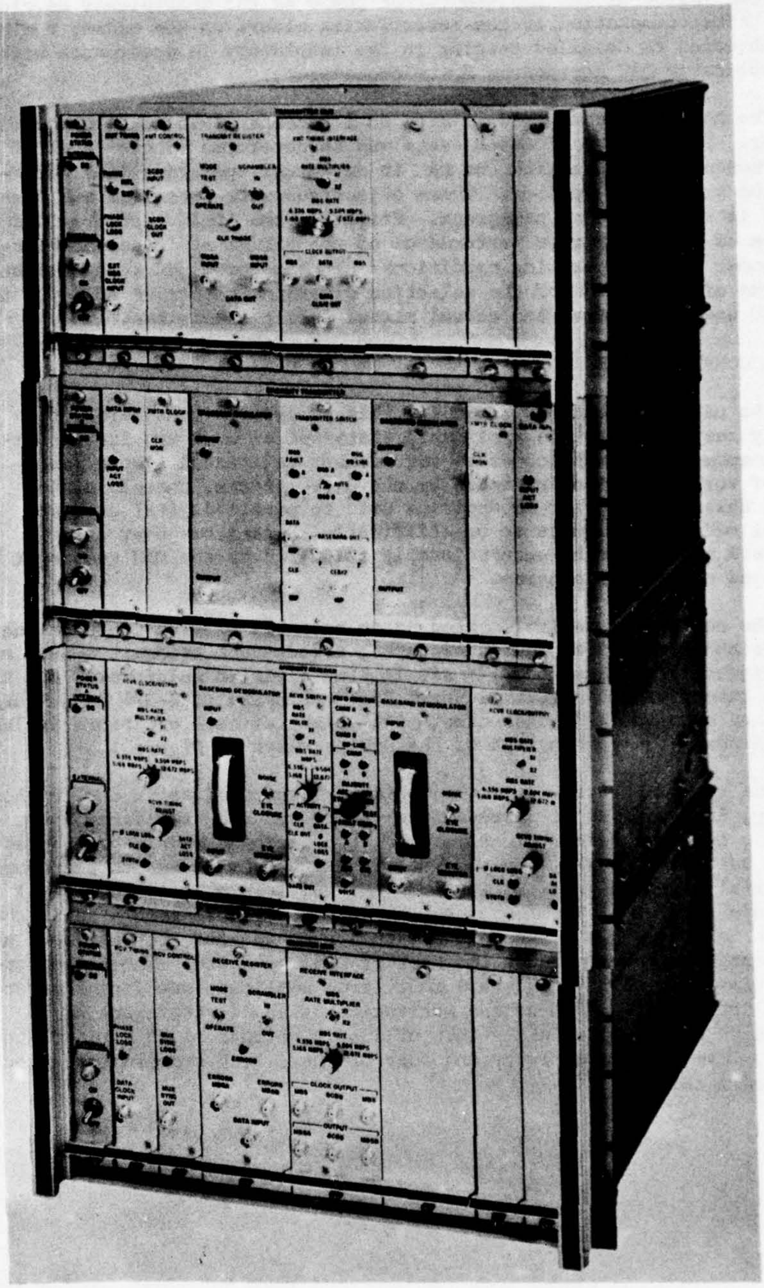


Figure 1. Digital Applique Unit

The receive modem unit was implemented to provide dual diversity operation. It consists of a receiver switch module, a performance monitor module, two baseband demodulator modules, two receiver clock/output modules and an associated power supply. The receive modem serves to convert the received four level amplitude waveform to an equivalent serial binary representation. The receiver switch module is designed to apply the output of either modem (designated as Channel A or Channel B) to the input to the demultiplexer depending on the relative magnitude of the AGC, eye pattern closure and out-of-band noise level in the associated channel and circuit failures. Specifically, switching from one modem to the other is effected by the following failure conditions; loss of supply voltage, low signal level at the input to the receive modem, loss of data signal at the output of the modem, and loss of clock phase lock.

The transmit timing module, the transmit control module, the transmit register module, the transmit timing interface module, and the associated power supply comprise the circuit complement of the multiplexer. The multiplexer serves to synchronously time division multiplex a single 192 Kbps service channel bit stream (SCBS) with one or two mission bit streams (MBS). The allowable rate for each (1 or 2) MBS input may be either 3.168 Mbps, 6.336 Mbps, 9.504 Mbps or 12.672 Mbps. Transmit timing is derived from an internally located master oscillator or as a switchable option from an external source (MBS data source or station clock which varies at the MBS rate).

A total of four functional modules and the associated power supply comprise the demultiplexer. The functional modules are designated receive timing, receive control, receive register and receive interface. The function of the demultiplexer is to provide the inverse of the operations performed by the multiplexer; i.e., the isolation and separation of SCBS and MBS which is received in a time division multiplexed format. The demultiplexer delivers to the respective data sinks the recovered MBS signal(s) and associated timing and the recovered SCBS and its associated timing.

The preceding discussion was intended as a cursory description of the DAU equipment. A much more comprehensive description of the DAU is presented in Section 3. A delineation of the pertinent performance characteristics of the DAU is contained in Table 1. The technical characteristics of the DAU are presented in Table 2.

TABLE 1. DAU PERFORMANCE CHARACTERISTICS

Compatible Radio Sets	LC-4/LC-8 AN/FRC-155, 156...162 AN/FRC-80 AN/FRC-109 Others*
Bit Packing Density	2 Bps/Hz** or 1 Bps/Hz
Bit Error Rate	5×10^{-9} for E_b/N_o = 26 dB** (with scrambler) at 2 Bps/Hz
Type of Diversity	Dual, post-detection selection
Degradation of BER Due to Diversity Switch	None; switch is of the "hitless" type
Size of Randomizer	20 stages
Sync Acquisition Time	Less than 50 milliseconds for $P_e = 10^{-3}$
Mean Time to Loss of Sync	24 hours minimum at a BER = 10^{-2}
Diversity Switching Criteria	Circuit failures AGC Eye pattern closure Out-of-band noise
Transmit Timing Mode	
Primary	Internal DAU master clock
Optional (switching)	MBS or station timing (MBS rate)
BER Performance Floor (DAU in Back-to-Back Configuration)	Better than 5×10^{-10}

* FM microwave radio sets which meet the minimum specified performance standards.

** Achievable with compatible radio sets.

TABLE 2. DAU TECHNICAL CHARACTERISTICS

GENERAL	
Number of Units/System	4
Unit Designation	Multiplexer Redundant Transmitter Diversity Receiver Demultiplexer
Prime Power	115 VAC ±10%, 60 Hz ±5%
AC Current Drain	
Multiplexer	2.2 amperes nominal
Redundant Transmitter	1.8 amperes nominal
Diversity Receiver	1.7 amperes nominal
Demultiplexer	2.1 amperes nominal
Size of Unit	8-3/4" high x 19" wide x 19" deep
Weight	Less than 55 pounds each unit
Operating Temperature Range	$0^{o}C$ to $+50^{o}C$
DATA SOURCE/DAU INTERFACE	
Rate	
SCBS	192 Kbps (1)
MBS	3.168 Mbps (1 or 2) 6.336 Mbps (1 or 2) 9.504 Mbps (1 or 2) 12.672 Mbps (1 or 2)
Format	
MBS and SCBS	Serial Binary; NRZ-L
Input Level	1 to 5 volts peak-to-peak around ground
Input Connector	BNC
Input Impedance	75 ohms ±10% unbalanced

TABLE 2. DAU TECHNICAL CHARACTERISTICS (continued)

Waveform	Square wave; rise and fall time 10% maximum of bit length
Timing Relationship (MBS Timing Option)	Trailing edge of clock signal is within ±10% of the center of data baud
Jitter (MBS Timing Option)	Peak timing to peak data excursion of less than 10% of the data baud interval
Internal Clock Stability	±10 ppm
<u>DAU/RADIO TRANSMITTER INTERFACE</u>	
Output Level	1 volt peak-to-peak nominal
Waveform	Four level AM
Impedance	75 ohms ±10% unbalanced
Return Loss	Greater than 20 dB
Connector	BNC
Frequency Response (f = 1/4 MBS rate)	-3 dB relative to DC response value
<u>RADIO RECEIVER/DAU INTERFACE</u>	
Input Level	1 volt peak-to-peak nominal
Waveform	Four level AM
Input Impedance	75 ohms ±10% unbalanced
Return Loss	Greater than 20 dB
Connector	BNC
Frequency Response (f = 1/4 MBS rate)	-3 dB relative to DC response value
AGC Voltage	Variable range (function of Radio Set)

TABLE 2. DAU TECHNICAL CHARACTERISTICS (continued)

DAU/DATA SINK INTERFACE

Output Level (MBS and SCBS)	2 volts peak-to-peak nominal across 75 ohm termination
Format (MBS and SCBS)	Serial binary; NRZ-L
Rate	
SCBS	192 Kbps (1)
MBS	3.168 Mbps (1 or 2) 6.336 Mbps (1 or 2) 9.504 Mbps (1 or 2) 12.672 Mbps (1 or 2)
Output Impedance	75 ohms ±10% unbalanced
Output Connector	BNC
Waveform	Square wave; rise and fall time 10% maximum of bit length
Jitter	Peak timing to peak data excursion of less than 5% of the data baud interval
Data/Timing Relationship	Positive-to-negative transition of output timing signal is within ±10% of data baud center

1.5 DELIVERABLE ITEMS

In accordance with the statement of work and the associated amendments, the following items were delivered to RADC:

ITEM	DATE DELIVERED
Design Plan	1 June 1975
Acceptance Test Plan	30 September 1975

ITEM	DATE DELIVERED
Dual Modem*	6 October 1975
DAU Equipment	1 December 1975
Final Report	15 January 1976
Handbook	30 January 1976

* Dual Modem returned to Aeronutronic Ford after completion of field testing for modification to permit operation at new MBS rates.

SECTION 2

DISCUSSION OF TECHNICAL REQUIREMENTS

2.1 INTRODUCTION

In the statement of work PR No. C-5-2069 and its associated Amendment No. 3 dated 1975 March 4, the requirements for the Digital Applique Unit (DAU) are presented and described. These requirements are considered to be straightforward and well defined. No exceptions or deviations were taken to the requirements as stated.

In the engineering Design Plan submitted as a contractual item on June 30, 1975, the impact of these technical requirements on the system and circuit design was discussed. It is the purpose of this section to summarize, modify and elaborate on the conclusions formulated in the design plan. The modification and expansion of the design plan conclusions are necessitated by changes in the requirements which became effective after completion of the design plan.

2.2 TYPE OF MODULATION

It is specified in paragraph 4.8.3.1 of Amendment No. 3 dated 1975 March 4, of the statement of work that the "Modulation technique for this paragraph (4.8.3) shall be four level AM". The use of four-level AM is heartily endorsed because of the comparatively high bandwidth utilization efficiency realizable when used in conjunction with a frequency modulation type radio equipment. Spectral occupancy of the transmitted waveform can be controlled with a four-level AM/deviator configuration with an essentially transparent transmitter output filter by the judicious setting of the deviation ratio. In addition, because of the constant amplitude characteristics of the frequency modulated waveform, linearization of the system amplifier stages is not required. Furthermore, the generation of the four-level AM signal from a binary waveform and the inverse operation to obtain a serial binary stream can be accomplished by means of D/A and A/D converters, which are relatively simple in design.

2.3 MBS RATES

In paragraph 4.8.3 of the statement of work (Amendment No. 3, 1975 March 4), it is stated that the DAU will accept one or two mission bit streams, each of which will run at a nominal 13 Mbps rate. This requirement was subsequently superseded by a specification which stated

that the DAU shall provide and accept one or two mission bit streams of the following rates:

3.168 Mbps
6.336 Mbps
9.504 Mbps
12.672 Mbps

When two mission bit streams are applied to the DAU, they will be synchronous and of equal rates.

Based on the original specification, the DAU was only required to accommodate a total of two mission bit stream rates; i.e., 12.672 Mbps and 25.344 Mbps. The modified MBS input rate requirement, however, increases the total number of mission bit stream rates which must be accommodated by the DAU to six. These are:

3.168 Mbps
6.336 Mbps
9.504 Mbps
12.672 Mbps
19.008 Mbps
25.344 Mbps

Since operation at any of the specified MBS rates is required to be switch selectable, the increase in the number of allowable MBS rates impacts directly on the complexity of the transmitter and receiver clock modules. The impact can, however, be minimized if the final transmission rates can be constrained to possess the same inter-rate proportionality relationship as prevails between the total MBS rates.

Referring to the list of total MBS rates, it can be noted that 6.336 Mbps is exactly equal to twice the lowest MBS rate of 3.168 Mbps. Similarly, 9.504 Mbps is exactly equal to three times 3.168 Mbps and so forth. This inter-rate relationship is conducive to the use of digital frequency division type frequency synthesis techniques. For example, timing for all of the specified MBS input rates, 3.168 Mbps, 6.336 Mbps, 9.504 Mbps and 12.672 Mbps can be derived from a 76.032 MHz master oscillator by using digital count-downs of 24, 12, 8 and 6, respectively. Hence, in the internal timing mode of operation the MBS timing requirement can be satisfied basically by the use of a 76.032 MHz master oscillator in conjunction with a programmable counter.

2.4 TRANSMISSION RATE

In paragraph 2.6 of this report, it is indicated that the preferred transmission rate for a 3.168 Mbps input MBS rate is 3.456 Mbps. This conclusion was derived primarily from time division multiplexing considerations. As indicated in paragraph 2.3, the impact of the multiple MBS rate requirement can be minimized by constraining the inter-rate proportionality relationship of the transmission rates to be identically the same as the corresponding inter-rate relationship of the input MBS rates. Imposing this constraint yields the following values of transmission rates for the DAU:

TABLE 3. TRANSMISSION RATES

MBS Input #1	MBS Input #2	Total MBS Rate	Transmission Rate
3.168 Mbps	-	3.168 Mbps	3.456 Mbps
3.168 Mbps	3.168 Mbps	6.336 Mbps	6.912 Mbps
6.336 Mbps	-	6.336 Mbps	6.912 Mbps
6.336 Mbps	6.336 Mbps	12.672 Mbps	13.824 Mbps
9.504 Mbps	-	9.504 Mbps	10.368 Mbps
9.504 Mbps	9.504 Mbps	19.008 Mbps	20.736 Mbps
12.672 Mbps	-	12.672 Mbps	13.824 Mbps
12.672 Mbps	12.672 Mbps	25.344 Mbps	27.648 Mbps

The six required transmission rates, 3.456 Mbps, 6.912 Mbps, 10.368 Mbps, 13.182 Mbps, 20.736 Mbps and 27.648 Mbps, as with the MBS timing, can be derived from a single oscillator/programmable counter combination. Using a 82.944 MHz oscillator and programmable counts of 24, 12, 8, 6, 4 and 3, the indicated final transmission rate timing can be readily obtained.

One of the constraints impacting the selection of the final transmission rates was an upper bound of 28 Mbps on the highest rate. This requirement was necessary in order to allow the attainment of 2 bits per Hertz packing density at the highest transmission rate, based on a maximum allowable channel assignment of 14 MHz. The highest transmission rate of 27.648 Mbps, which resulted from using the same inter-rate relationship for the transmission rate as prevails for the input MBS rates, is responsive to the upper bound transmission rate constraint.

2.5 SCBS RATE

In Amendment No. 3, dated 1975 March 4, of the statement of work, it is specified that the DAU shall accept and provide an orderwire bit stream which runs at a 192 Kbps rate. This rate requirement for the orderwire bit stream should not and did not present any undue problems

in the design of the DAU. In fact, a favorable proportionality relationship exists between the specified MBS rates and SCBS rate which was exploited to yield a relatively simple multiplexer design.

If we define M and N as the number of MBS and SCBS digits in a given frame period T, we can write

$$T = M\,\tau_{MBS} = N\,\tau_{SCBS}$$

or

$$T = \frac{M}{f_{MBS}} = \frac{N}{f_{SCBS}}$$

and

$$\frac{M}{N} = \frac{f_{MBS}}{f_{SCBS}}$$

For a SCBS rate of 192 Kbps and specified MBS rates the corresponding M/N ratio is as follows:

TABLE 4. MBS RATE PROPORTIONALITY CONSTANTS

MBS Rate	M/N	K = M/11
3.168 Mbps	33/2	3
6.336 Mbps	66/2	6
9.504 Mbps	99/2	9
12.672 Mbps	132/2	12

It should be noted that for N equal to 2 the values of M, for all of the MBS rates are multiples of 11, as defined by the letter K in the above table. This relationship suggests the possibility of using a multiplexing format predicated on the interleaving of blocks of 11 data digits with the orderwire and frame sync code word. This approach was evaluated, as were other multiplexing formats, and was subsequently selected as an effective solution to the basic multiplexing formatting problem.

2.6 MULTIPLEXING FORMAT

It was indicated in the preceding paragraph that the specified SCBS rate of 192 Kbps bears an integer relationship to the MBS rates which are expressible as multiples of 11. At the lowest MBS rate, 3.168 Mbps, a frame period defined by an interval equal to the duration of two SCBS digits, can accommodate three 11-digit blocks of MBS data.

In the interest of simplicity of implementation, it is desirable if the interleaving of the service channel and mission bit streams can be accomplished with some degree of periodicity or uniformity. This implies that the multiplexed sequence within a frame be divisible into an integer number of equal segments and that the number of segments be equal to the sum of the frame sync and service channel digits in a given frame.

The afore cited conditions of periodicity can be satisfied for the 3.168 Mbps MBS input rate case if a single frame sync pulse is allotted to each frame period T. If this were done, the format of a basic multiplexed frame would be as depicted in Figure 2. The resultant transmission rate with this arrangement is:

$$R_T = \frac{N_{MBS} + N_{SCBS} + N_{SYNC}}{N_{MBS}} \times R_{MBS}$$

where

N_{MBS} = Number of MBS digits per frame

N_{SCBS} = Number of SCBS digits per frame

N_{SYNC} = Number of frame sync pulses per frame

which for a single 3.168 Mbps input to the DAU yields

$$R_T = \frac{33 + 2 + 1}{33} \times 3.168 \text{ Mbps}$$

or

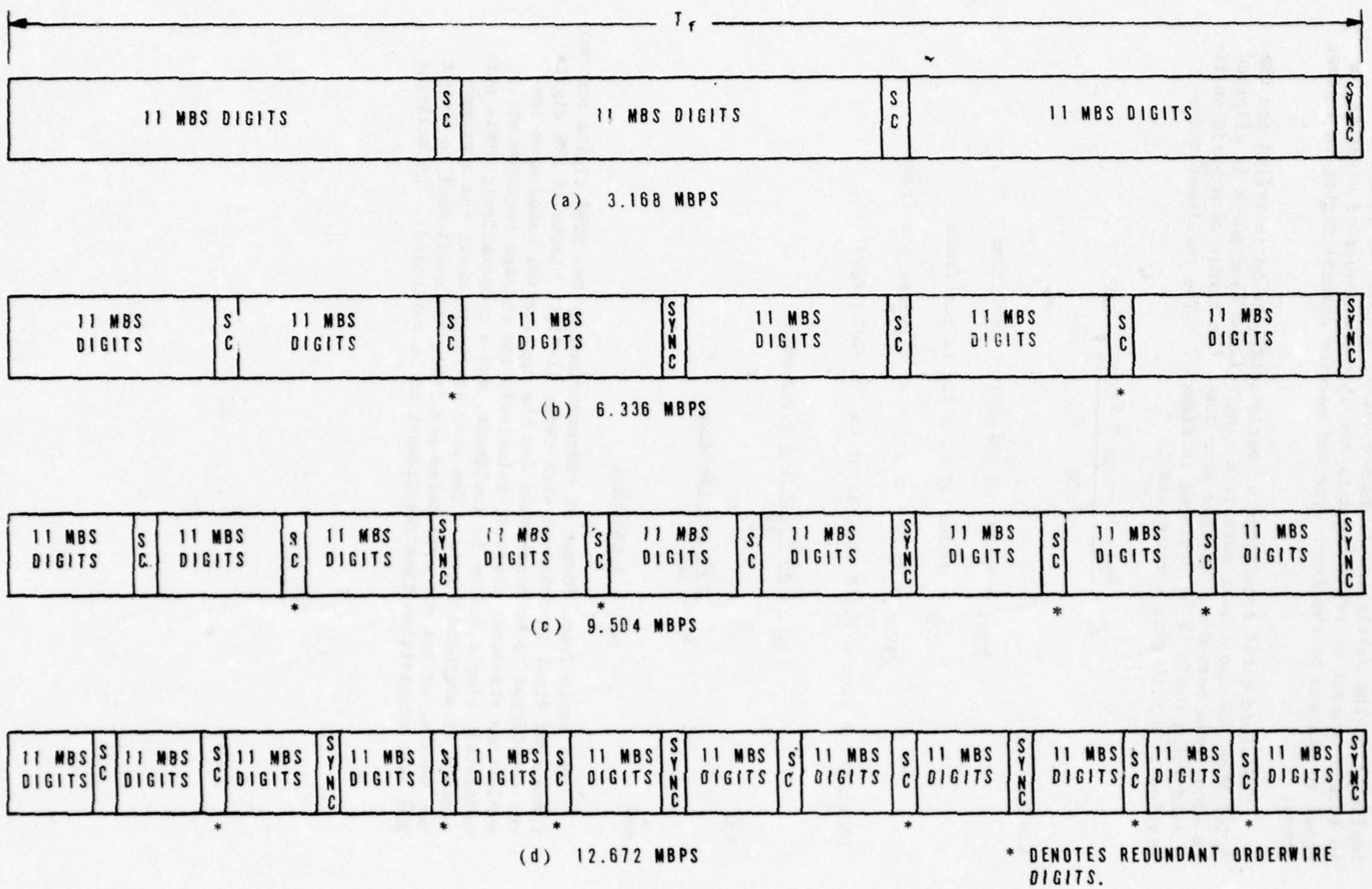
$$R_T = \frac{36}{33} \times 3.168 \text{ Mbps}$$

and

$$R_T = 3.456 \text{ Mbps}$$

The basic frame format as characterized by two SCBS digits and one frame sync digit interleaved with three 11-digit blocks of MBS digits was considered to be acceptable for the application based upon the evaluation standards imposed; relatively low storage requirements, moderately simple design to implement, and a comparatively small percentage of overhead digits. The only hesitancy about the approach was whether or not one sync pulse per frame was sufficient to permit the sync acquisition time requirement to be satisfied. The analysis

Figure 2. Multiplexing Format - Single MBS Input



conducted indicated that no difficulty should be encountered with a single sync pulse per frame in achieving frame synchronization in less than the 50 milliseconds specified.

In an endeavor to minimize the complexity of the timing circuits of the DAU, it was decided to constrain the multiplexer output rates to possess the same inter-rate proportionality relationship as prevails for the specified input MBS rates. Relative to the lowest MBS rate of 3.168 Mbps, the proportionality constants are 2, 3, 4, 6 and 8 for the total MBS rates of 6.336 Mbps, 9.504 Mbps, 12.672 Mbps, 19.008 Mbps and 25.344 Mbps, respectively. Using these same proportionality constants for the transmission rates relative to 3.456 Mbps yields rates of 6.912 Mbps, 10.368 Mbps, 13.824 Mbps, 20.736 Mbps and 27.648 Mbps.

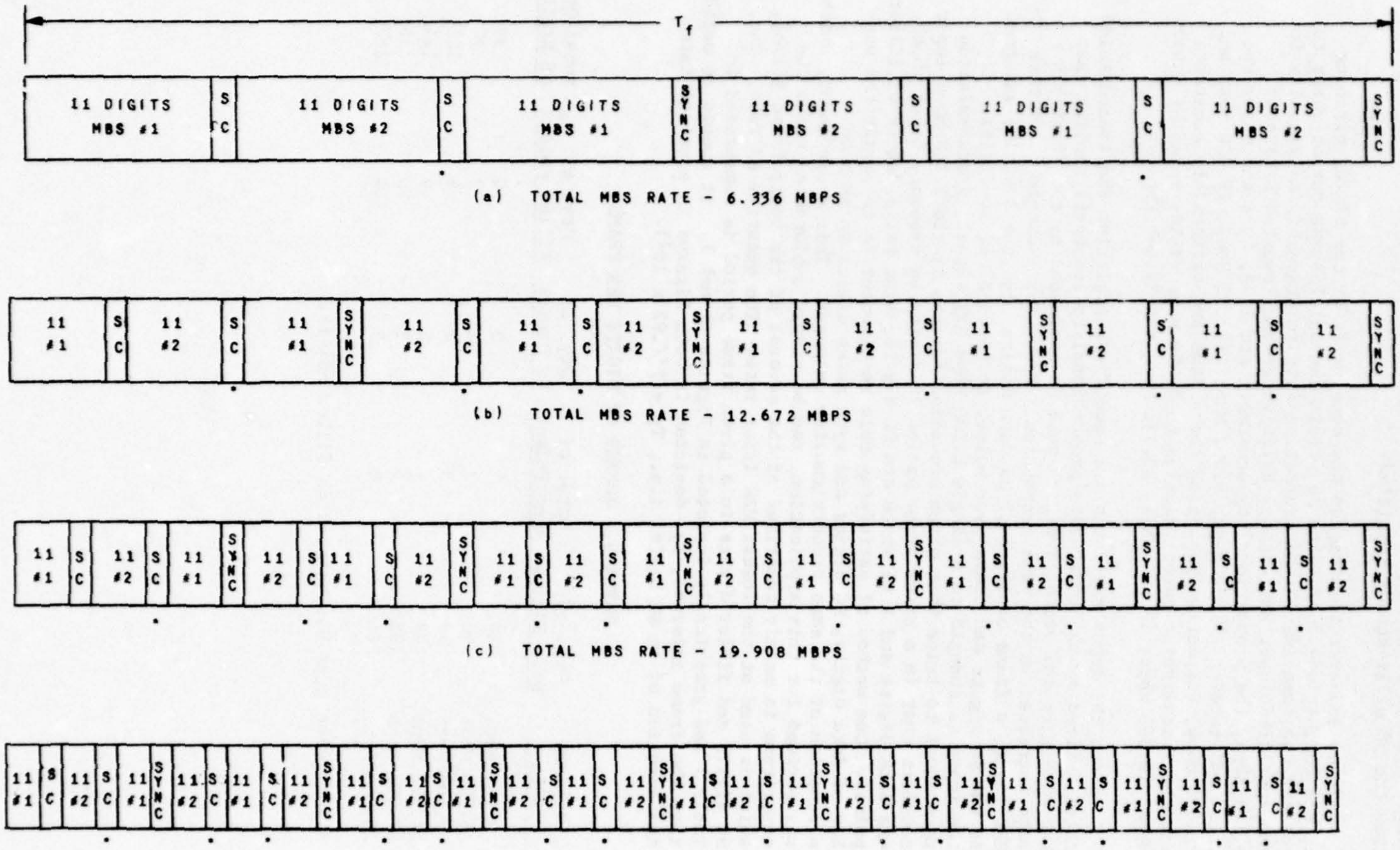
Since the input MBS rates are specified, achieving the transmission rates defined by the inter-rate proportionality constants implies that the SC digits and overhead digits must be increased as the input MBS rate increases in the same proportion. Thus, for a single 3.168 Mbps MBS input, a frame consists of 33 data digits plus the 3 digits assigned to the SC digits and frame sync pulse, for a total of 36 digits. If the input is changed to a single 6.336 Mbps MBS signal, a transmission rate equal to twice that which prevailed for the single 3.168 Mbps input requires that in a given frame period 72 digits be present; 66 of which are data digits and 6 of which are SC digits, sync pulse digits or filler pulses. One method of satisfying this requirement is to permit the number of data digits, SC digits and sync pulse digits to each be a function of the same proportionality constant. This arrangement, which was pursued for this application, can be simply implemented since the superframe is merely comprised of the several of the basic frame format, which is used at the lowest MBS input rate. The quantity of data, sync, SC digits and filler digits in a given frame period is summarized in Table 5 and graphically depicted in Figures 2 and 3. It should be noted that the frame interval, T_f, depicted in both Figures is equal to twice the duration of an SC digit; i.e., $T_f = 2/(192 \times 10^3)$.

TABLE 5. NUMBER OF DIGITS PER FRAME

Total MBS Rate	Qty. of Data Digits	Qty. of Sync Pulses	Qty. of SC Digits	Qty. of Filler Pulses *	Total Qty. of Digits
3.168 Mbps	33	1	2	0	36
6.336 Mbps	66	2	2	2	72
9.504 Mbps	99	3	2	4	108
12.672 Mbps	132	4	2	6	144
19.008 Mbps	198	6	2	10	216
25.344 Mbps	264	8	2	14	288

* Redundant SCBS digits used as filler pulses.

Figure 3. Multiplexing Format - Dual MBS Input



(a) TOTAL MBS RATE - 6.336 MBPS

(b) TOTAL MBS RATE - 12.672 MBPS

(c) TOTAL MBS RATE - 19.908 MBPS

(d) TOTAL MBS RATE - 25.344 MBPS

* DENOTES REDUNDANT ORDER-WIRE DIGITS

During the program, it became evident that subsequent DAU equipments should interface with existing second-level multiplexers whose output rate is based upon a N x 3.232 Mbps relationship. Table 6 summarizes the DAU input and output rates reflecting the impact of the N x 3.232 relationship.

TABLE 6. DAU INPUT AND OUTPUT RATES

MBS Rate (Mbps)	No. of MBS Inputs	Modem Input Rate (Mbps)	Modem Baud Rate ($X10^6$)
3.232	1	3.456	1.728
3.232	2	6.912	3.456
6.464	1	6.912	3.456
6.464	2	13.824	6.912
9.696	1	10.368	5.184
9.696	2	20.736	10.368
12.928	1	13.824	6.912
12.928	2	27.648	13.824

2.7 SYNC ACQUISITION TIME

As indicated in the preceding paragraph, a frame of multiplexed data consists of three 11-digit blocks of data in which single SCBS digits are interleaved between the first and second block and between the second and third block and a single frame sync pulse follows the third block of data. The frame sync digit is alternated from frame to frame between a logic one state and a logic zero state. The sync acquisition process entails the establishment of the timing relationship which yields an aperture gate that is in time coincidence with the occurrence of the frame sync digits. A sync code word is comprised of M contiguous digits of the alternating one/zero pattern.

The search procedure entails the observation of every 36th bit of the multiplexed sequence until M such observations are made. If the format of the M digits thus observed does not satisfy the acquisition criterion, the aperture is displaced by an interval equal to the duration of one multiplexed digit and the observation procedure is repeated. In the worst case, 72 such observations must be made before the sync code word is recognized on the 72nd observation. The acquisition time can be expressed as:

$$T_A = M\ (36)\ (72)\ \tau$$

where:

M = Length of sync code word

36 = Number of digits per frame

72 = Number of observations for worst case condition

τ = Duration of multiplexed digit

Referring to the expression for the acquisition time, it should be apparent that for a given value of M, the acquisition time is directly proportional to the duration of a digit or inversely proportional to the rate of the multiplexed signal. Consequently, the longest acquisition time, as one may intuitively deduce, will occur at the lowest rate; 3.456 Mbps. Assuming T_A equals 50 msecs, letting τ be equal to 1/3.456 x 10^6 and solving for M we obtain

$$M = \frac{(50)(10^{-3})(3.456 \times 10^6)}{(72)(36)}$$

and

$$M = 66.67$$

This result indicates that a frame sync code word as long as 67 digits could be used and still permit, in the worst case, frame acquisition to occur within 50 msec. The value of M obtained with this equation is only an upper bound and much shorter code words can be used without compromising performance provided the associated acquisition and false alarm probabilities are within acceptable limits. It was, therefore, decided as an initial trial value to use a value of M equal to 32.

With a bit error rate of 10^{-3}, the probability of sync acquisition, P(s), assuming a 32 digit frame code word is approximately 96.8 percent if no errors in the sync code word is permitted. If we desire to increase the probability of sync acquisition in the indicated time interval to a higher value we must permit sync to be declared even though some of the digits of the sync code word are in error. The resultant increase in the probability of sync acquisition is obtained by a corresponding increase in the probability of declaring false sync, P(dfs). As a rule of thumb, the best compromise for the number of errors permitted is that which results in the probability of acquisition being approximately equal to the probability of not declaring false sync; i.e.,

$$P(s) = P(ndfs) = 1 - P(dfs)$$

The procedure for determining an optimum value for the number of errors, n, permitted in a sync code word without destroying the validity of the code word is to select a value for n and then compute the two probability functions, P(s) and P(ndfs). The process is repeated until the appropriate equality relationship between the two functions is established.

The probability of having at least m-n correct digits out of a sequence of m digits can be expressed as:

$$P(s) = \sum_{n=o}^{n} \binom{m}{m-n} p^{m-n} q^{n}$$

where

$\binom{m}{m-n}$ = Number of different combinations of m objects taken m-n at a time

p = Probability of a digit occurring correctly

q = 1-p = Probability of a digit occurring incorrectly

The computed probability of acquisition as a function of the number of code word errors for various error rates is presented in Table 7.

Since the data signal is random, the probability is finite that some formats of 32 data digits will be mistaken for the sync code word. When this occurs, a false sync declaration condition will prevail. The probability of declaring false sync in a single observation is

$$P_1(dfs) = \sum_{n=o}^{r} \binom{m}{m-n} (p_1)^{m-n} (p_o)^{n}$$

where

r = The maximum number of errors allowed in the sync code word

m = Sync code word length (assumed to be 32)

p_1 = Probability of occurrence of a one (assumed to be 1/2)

p_o = Probability of occurrence of a zero (assumed to be 1/2)

For random data we can assume $p_o = p_1 = 1/2$ and the above expression, for a 32 digit code word, reduces to

$$P_1(dfs) = \left(\frac{1}{2}\right)^{32} \sum_{n=o}^{r} \binom{32}{32-n}$$

TABLE 7. PROBABILITY OF ACQUISITION FOR VARIOUS DIGIT ERRORS

Number of Allowed Code Word Errors	P(s)*		
	$p = 0.9$ $q = 0.1$	$p = 0.99$ $q = 0.01$	$p = 0.999$ $q = 0.001$
0	0.0343	0.7248903	0.9684911
1	0.1564	0.9593174	0.9995138
2	0.3667	0.9960066	0.9999951
3	0.6003	0.9997125	1.0000000
4	0.7885	0.9999839	1.0000000
5	0.9056	0.9999993	1.0000000
6	0.9642	1.0000000	1.0000000
7	0.9883	1.0000000	1.0000000
8	0.9967	1.0000000	1.0000000
9	0.9992	1.0000000	1.0000000
10	0.9998	1.0000000	1.0000000

* Code word length is equal to 32 digits.

The probability of not declaring false sync per observation is simply the complement of the probability of declaring false sync; i.e.,

$$P_1(\text{ndfs}) = 1 - P_1(\text{dfs})$$

In the worst case, as indicated above, 72 such observations will have to be made before sync is declared. Therefore, the probability of not declaring false sync in the worst case is

$$P_t(\text{ndfs}) = \left[P_1(\text{ndfs})\right]^{72}$$

or

$$P_t(\text{ndfs}) = \left[1 - P_1(\text{dfs})\right]^{72}$$

A tabulation of $P_1(\text{dfs})$, $P_1(\text{ndfs})$ and $P_t(\text{ndfs})$ as a function of the number of digit errors allowed in the sync code word is presented in Table 8. As can be expected, the probability of not declaring false sync, $P_t(\text{ndfs})$, decreases in value with increasing allowable errors in the sync code word.

Based on an evaluation of the calculations presented in Tables 7 and 8, the decision was made to permit at least two errors in the frame sync code word. This results in at least five nines (0.99999) for both the probability of sync acquisition, P(s), and the probability of not declaring false sync, $P_t(\text{ndfs})$, assuming an error rate of 10^{-3} and a 32 bit sync code word. As can be noted in Table 8, allowing at least two errors in a 32 bit sync code word yields a probability of acquisition, P(s), of better than 99 percent even for an error rate of 10^{-2}.

It should be noted that for a 32 bit sync code word the acquisition time for the worst case condition is

$$T_A = \frac{(32)(36)(72)}{3.456 \times 10^6} = 24 \text{ msec}$$

This value of acquisition time is predicated on the evaluation of a complete 32 digit sync code word for each observation to determine if the received code word is valid. However, in practice as soon as three or more errors are detected in the sync code word, the observation aperture will be changed and the examination of a new potentially valid sync code word will be initiated. As a consequence, the probability is extremely small that the worst case acquisition time of 24 msec will be observed, when the DAU is operational.

TABLE 8. FALSE SYNC PROBABILITIES

Number of Allowed Errors in Code Word	P_1(dfs)	P_1(ndfs)	P_t(ndfs)
0	2.3283×10^{-10}	1.0000000	1.0000000
1	7.6834×10^{-9}	1.0000000	0.9999995
2	1.2316×10^{-7}	0.9999999	0.9999913
3	1.2780×10^{-6}	0.9999987	0.9999093
4	9.6506×10^{-6}	0.9999903	0.9993150
5	56.5371×10^{-6}	0.9999435	0.9959938
6	267.5264×10^{-6}	0.9997325	0.9811824
7	1.0512×10^{-3}	0.9989488	0.9280456
8	3.500×10^{-3}	0.9965000	0.7796300
9	10.0308×10^{-3}	0.9899692	0.4888093
10	25.0512×10^{-3}	0.9749488	0.1650853

2.8 MEAN TIME TO LOSS OF SYNC

In the event that a valid sync code word is observed and sync declared, the demultiplexer will automatically be switched from the acquisition mode to the tracking mode. In the tracking, every 36th digit will be observed for the occurrence of a sync code digit. If noise induced errors are excessive, rejection of the true sync code word will subsequently occur resulting in the declaration of loss of sync and reinitiation of the acquisition mode. Similarly, if the initial acquisition was erroneously declared, the rejection of the false sync condition will occur in the tracking mode and the acquisition mode will be reinitiated.

Assume for the moment that a valid sync code word is received, examined and sync acquisition is declared. The demultiplexer is then switched to the tracking mode and the occurrence of subsequent sync code words is observed. If errors due to noise are occurring, we can define the probability of a valid sync word being received in the tracking mode as

$$P_T(s) = \sum_{s=o}^{r} \binom{m}{m-s} p^{m-s} q^s$$

where

$\binom{m}{m-s}$ = Number of different combinations of m objects taken m-s at a time

p = Probability of a digit occurring correctly

q = (1-p) = Probability of a digit occurring incorrectly

The probability that the first sync code word received *after initiation* of the tracking mode is, of course, $P_T(s)$. The probability of the first sync code word received after initiation of the tracking mode not being a valid sync code word is then equal to $1-P_T(s)$. This latter probability function also defines the probability of declaring loss of sync after the reception and observation of the first received code word following initiation of the tracking mode.

The probability of declaring loss of sync after reception of the second code word following the initiation of the tracking mode is

$$P_T(s) \left[1-P_T(s)\right]$$

The probability of declaring loss of sync after reception of the third sync code word is

$$P_T2(s)\left[1-P_T(s)\right]$$

and so forth. The average number of sync code words, Q, which can be received before declaring loss of sync is equal to the sum of the appropriately weighted probability of sync rejection; associated with each received sync code word following initiation of the tracking mode, divided by the total probability of rejection

$$Q = \frac{1}{P(R)}\left\{\left[1-P_T(s)\right] + 2\,P_T(s)\left[1-P_T(s)\right] + 3\,P_T^2(s)\left[1-P_T(s)\right] + \ldots\right\}$$

The weighting factors used reflect the number of sync code words received before loss of sync is declared at each decision time of the tracking mode. Since the total probability of rejection, P(R), is unity, we may write:

$$Q = \left[1-P_T(s)\right]\left[1 + 2P_T(s) + 3P_T^2(s) + 4P_T^3(s) + \ldots\right]$$

and

$$Q = 1 + P_T(s) + P_T^2(s) + P_T^3(s) + P_T^4(s) + \ldots$$

or

$$Q = \frac{1}{1 - P_T(s)}$$

Since every 36th digit of the multiplexed waveform is a sync pulse and the frame sync code word consists of 32 digits, 36 x 32 = 1152 digits must be received in order to assemble one complete frame sync code word. Consequently, the time interval, t_a, defined in the assembly of one complete frame sync word is

$$t_a = \frac{1152}{27.648 \times 10^6}$$

The mean time to loss of sync is merely the product of t_a and Q. Designating the mean time to loss of sync by the symbol T_M we may write

$$T_M = Qt_a$$

or

$$T_M = \frac{1152}{27.648 \times 10^6}\left[\frac{1}{1 - P_T(s)}\right]$$

Letting T_M = 24 hours and solving for P_T we obtain

$$P_T(s) = 1 - \frac{1152}{(27.648 \times 10^6)(24)(3600)}$$

and

$$P_T(s) = 0.9999999995$$

For an error rate of 1×10^{-2}, the above required $P_T(s)$ can be realized, if in the tracking mode, frame sync code words possessing up to and including 7 digits in error are considered to be valid. Permitting 7 digits to be in error in the tracking mode yields a mean time to loss of sync of almost exactly 24 hours. In the interest of providing some degree of margin, the demultiplexer was designed to accept as authentic a frame sync code word with up to and including 8 digit errors.

The expression for the mean time to the rejection of false sync, T_F, similar to the expression for T_M except that $P_T(s)$ is replaced by $P_T(dfs)$. Where $P_T(dfs)$ is the probability that the received sequence which was falsely interpreted as a valid sync code word, will be falsely interpreted again at the succeeding decision time. As with $P_1(dfs)$, the probability of declaring false sync, $P_T(dfs)$ is independent of the noise induced error rate and is strictly a function of the randomness of the generated data waveform. Therefore, for random data ($p_0 = p_1 = 1/2$) and a 32 digit sync code word

$$P_T(dfs) = (\tfrac{1}{2})^{32} \sum_{u=0}^{r} \binom{m}{m-u}$$

and

$$T_F = \frac{1152}{27.648 \times 10^6} \left[\frac{1}{1 - P_T(dfs)} \right]$$

with up to 8 digit errors allowed in the tracking mode

$$P_T(dfs) = 0.003500183$$

and

$$T_F = 41.8130 \text{ usecs}$$

As previously mentioned, the reception of 1152 digits is required for the multiplexing scheme employed in the DAU in order to assemble one complete frame sync code word. At the highest transmission rate of 27.648 Mbps, the time interval corresponding to 1152 multiplexed digits is approximately 42 usecs. This implies that if the demultiplexer is switched to the tracking mode due to a declaration of false sync, on the average loss of sync will be declared the next time the false sync word occurs.

2.9 CLOCK HOLD-OVER

It is anticipated that the DAU under actual operating conditions will occasionally experience a loss of the received data signal for comparatively long durations of time. While the duration of the outage will be variable and a function of the responsible phenomenon, an outage of two seconds appears to be a reasonable worst case condition. The primary concern regarding the signal outage is the possibility that the receiver clock will lose or gain a cycle during the outage interval which would assure a loss of BCI. It has been empirically determined that a maximum phase differential of 45 degrees in the clock signal, during the outage, will ensure that BCI will be maintained.

Temperature compensated crystal oscillators exhibiting temperature stability of 5×10^{-7} and short term stability of 1×10^{-9} used in conjunction with sample and hold circuits whose rate of drift is 3 MV/sec will meet the 45^{o} phase criterion at the highest data rate (two mission bit streams at 12.928 Mbps) for an interval of two seconds. At the lowest data rate (one mission bit stream at 3.232 Mbps), these components will maintain the phase differential for outages up to 13 seconds.

If the DAU receiver is eventually required to tolerate outages of received signal in excess of those previously mentioned, higher stability oscillators and perhaps more exotic sample and hold circuits will have to be employed. For example, if the temperature compensated crystal oscillators were replaced by oven stabilized crystal oscillators, the temperature stability and short term stability could be improved to 1×10^{-7} and 1×10^{-10}, respectively. Utilizing the same sample and hold circuit with these oscillators would assure that the maximum phase criterion could be met for the highest data rate (two mission bit streams at 12.928 Mbps) for an interval of 17 seconds, while at the lowest data rate (one mission bit stream at 3.232 Mbps), the tolerable interval would be in excess of 200 seconds.

It should be noted that the received signal outage investigation was undertaken using data rates which differ from those utilized on this program but that have a higher probability of utilization on subsequent programs.

2.10 SPECTRAL OCCUPANCY

The N-level normalized spectral density of a digital FM modulated waveform can be expressed according to Anderson and Salz[1] as

$$\frac{G(B)}{A^2T} = \frac{1}{N}\sum_{n=1}^{N}\left[\frac{1}{2}\,\frac{\sin^2\gamma_n}{\gamma_n^2} + \frac{1}{N}\sum_{m=1}^{N} B_{nm}\,\frac{\sin\gamma_n}{\gamma_n}\,\frac{\sin\gamma_m}{\gamma_m}\right]$$

where:

N = number of levels

$\gamma_n = (B - a_n K/2)\pi$

B = Normalized Frequency = $\frac{(W-W_c)}{2\pi}T$

$K = \frac{W_dT}{\pi} = 2f_dT = \Delta fT$

Δf = frequency separation between levels

T = symbol duration

$a_n = 2n - (N+1),\ n = 1, 2, \ldots, N$

$$B_{nm} = \frac{\cos(\gamma_n + \gamma_m) - C_a\cos(\gamma_n + \gamma_m - 2\pi B)}{1 + C_a^2 - 2C_a\cos 2\pi B}$$

$$C_a = \frac{2}{N}\sum_{n=1}^{N/2} \cos K\pi(2n-1)$$

The value of the normalized spectral density for N equal to 4 was calculated as a function of the normalized frequency, B, and various values of modulation index, K. The calculations were used to determine the values of K which satisfied the following condition:

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(1) "Spectra of Digital FM," R.R. Anderson and J. Salz, The Bell System Technical Journal, July-August 1965, pp. 1165 to 1189.

$$\frac{\int_{0}^{B=0.5} \frac{G(B)}{A^2T}\,dB}{\int_{0}^{\infty} \frac{G(B)}{A^2T}\,dB} \geqslant 0.99$$

The value of K, which satisfied this condition, will yield a packing density of 2 Bps/Hz. The calculations indicated that for values of K equal 0.16 and less packing densities of at least 2 Bps/Hz are achievable. These results were empirically confirmed using the modem section of the DAU.

The calculations were also used to determine the packing density as a function of the modulation index for a four-level system. This functional relationship is plotted in Figure 4.

2.11 BER PERFORMANCE

According to Mazo[(1)] et al, the probability of error of a n-level FSK signal for large signal to noise ratio, p, and small deviation ratio ($\Delta f/N < 1/2$) is given by

$$P_e = \frac{1}{(2\pi\rho)^{1/2}} \frac{\cot\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)}{\left[\cos\left(\pi\frac{\Delta f}{N}\right)\right]^{1/2}} \epsilon^{-2\rho \sin^2 \frac{\pi \Delta f}{2N}}$$

where

Δf = Level separation

N = 1/T = symbol rate

ρ = RF signal-to-noise ratio in frequency band B

B = Bandwidth according to Carson's rule; $B = N + (n-1)\Delta f$

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(1) Rate Optimization for Digital Frequency Modulation, J. E. Mazo, Harrison E. Rowe and J. Salz; Bell System Technical Journal, November 1969, pp. 3021 to 3029.

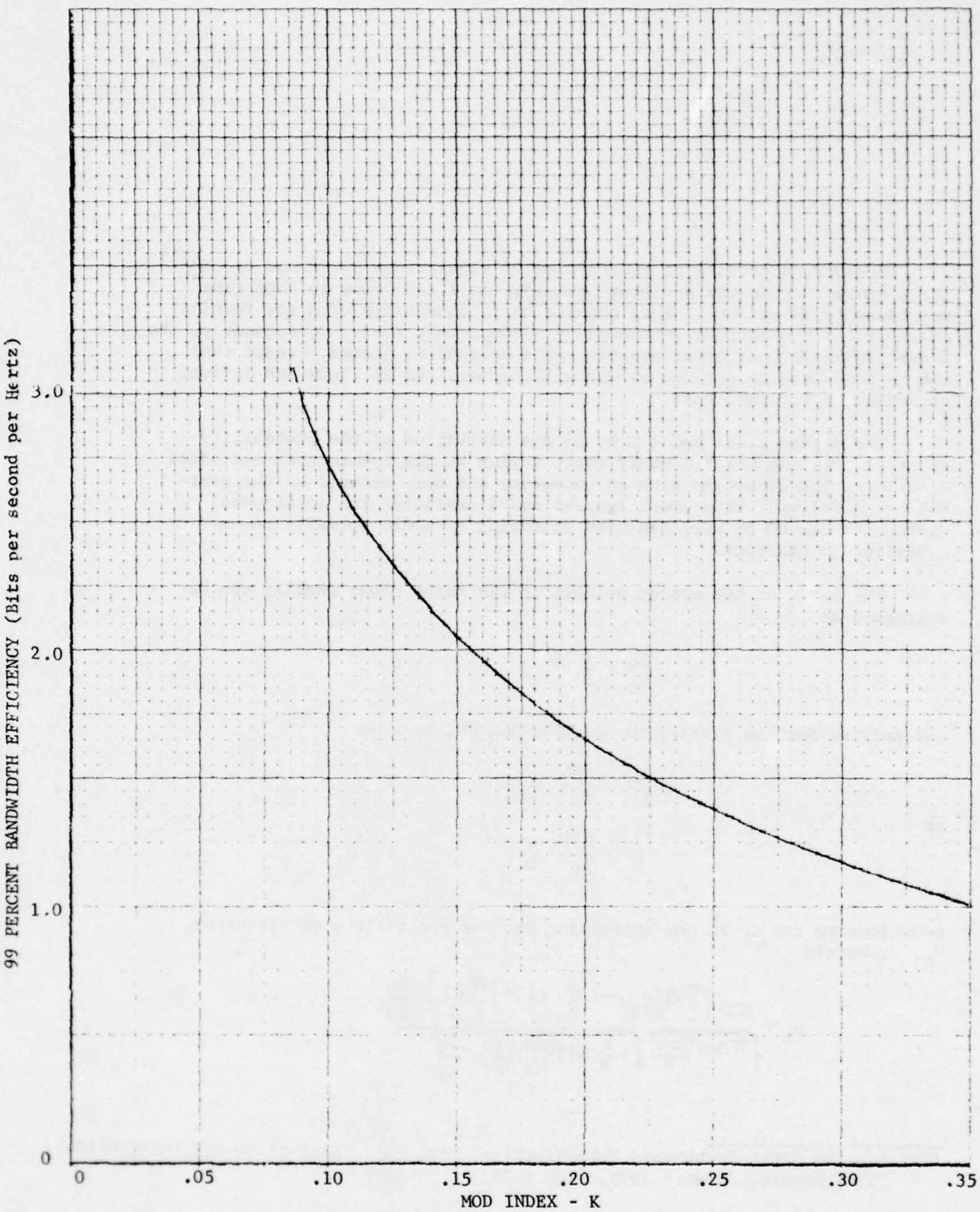


Figure 4. Bandwidth Efficiency vs. Mod Index for 4-Level FM

However, according to the results of simulations performed by CNR[1] for a quaternary format a filter bandwidth of 1.125 times the bit rate was found to be optimum. This conclusion is compatible with the results of empirical evaluations conducted by Aeronutronic Ford. Consequently, the above probability of error equation will be used as stated, except that the RF bandwidth as defined by CNR will replace the RF bandwidth defined according to Carson's rule.

The mathematical model used in the derivation of the probability of error, P_e, assumes frequency shift keying at the transmitter and ideal discrimination detection with an integrate and dump circuit as the post-detection filter. This model ignores non-linearities and intersymbol distortion caused by non-idealized filtering as would normally be encountered in practice.

The ratio of the energy per bit to the noise power density can be expressed as

$$\frac{E_b}{N_o} = \frac{1}{2} BT$$

and solving for the carrier-to-noise ratio, ρ, we have

$$\rho = \frac{2E_b}{N_o} \frac{1}{BT}$$

or

$$\rho = \frac{2E_b}{N_o} \frac{N}{B}$$

Substituting for ρ in the expression for the probability of bit error, P_e, we obtain

$$P_e = \frac{\cos\left(\frac{\pi}{2}\frac{\Delta f}{N}\right) \epsilon^{-4 \frac{N}{B} \sin^2\left(\frac{\pi}{2}\frac{\Delta f}{N}\right) \frac{E_b}{N_o}}}{\sqrt{\pi \cos \frac{\pi \Delta f}{N}} \sqrt{4 \frac{N}{B} \sin^2\left(\frac{\pi}{2}\frac{\Delta f}{N}\right) \frac{E_b}{N_o}}}$$

(1) Line of Sight Techniques Investigation, CNR, Inc., RADC-TR-74-330,(AD#A006104), Final Report, January 1975, page 4-14.

It was empirically determined that 2 Bps/Hz packing density can be achieved with four level FSK modulation using a modulation index, $\Delta f/N$, equal to 0.1591. Using this value of modulation index and B equal to (1.125)(2N) the probability of bit error reduces to

$$P_e = \frac{1.7695}{\sqrt{E_b/N_o}} \epsilon^{-0.1086 \frac{E_b}{N_o}}$$

A plot of Pe for various values of E_b/N_o is expressed in Figure 5. Also presented in the figure, for reference purposes, is a plot of the BER as a function of E_b/N_o which was obtained with the modem portion of the DAU operating with an Aeronutronic Ford LC-4D radio set. The measured data is degraded by approximately 2 dB relative to the theoretical performance curve as is to be expected due to the non-idealized transfer characteristics of actual operating systems and the idealized nature of the theoretical equation.

2.12 TRANSMIT TIMING

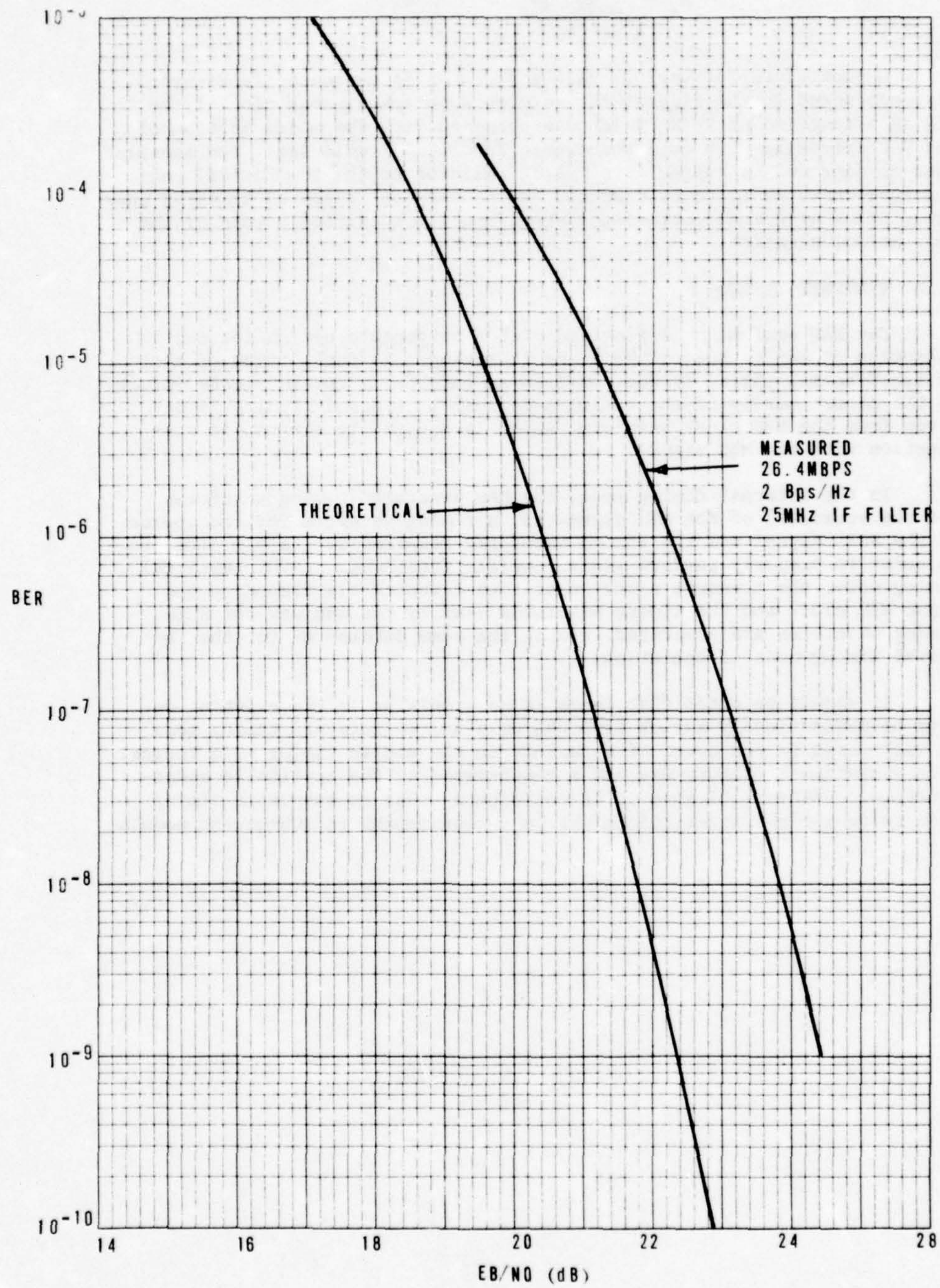
The DAU equipment is provided with a switchable option for the selection of the source of the transmit timing. In one setting of the switch, transmit timing is derived from an internally located master clock. In the other setting of the timing mode switch, transmit timing is derived from the MBS clock waveform, which is applied to the DAU in conjunction with the MBS signal.

In the internal timing mode, the DAU generates timing waveforms for the source(s) of the MBS signal(s), a timing waveform for the source of the SCBS signal and the timing waveforms required by the DAU circuits in order to properly perform their specific functions. In the external timing mode, the transmit clock generation circuits are slaved to the input MBS clock and the timing waveforms used by the DAU and the SCBS timing waveforms are generated in much the same fashion as for the internal timing mode of operation.

It should be noted that there is no provision in the existing design to automatically switch from the external to internal timing mode or vice versa in the event of a failure in the active timing mode source. This operational feature was not a requirement of the applicable specification. However, because it is anticipated that an automatic timing mode switching characteristic might be a requirement in subsequent models

Figure 5

BER VS E_b/N_o FOR 26.4 Mbps



of the DAU, the impact of incorporating this feature into the design was investigated. Of particular interest in this regard was the feasibility of maintaining bit count integrity with an automatic timing mode switching configuration.

Consider first the case in which the MBS clock signal is the source of the transmit timing. In this mode, DAU clock generation circuits are slaved to the MBS timing and, of course, the clock signals used in the DAU for the processing are phase coherent with the applied MBS waveform. A failure of the clock source, if it occurs, can occur in one of two ways. One type of failure would entail the loss of the timing waveform which is applied to the DAU, but no deterioration of the MBS signal itself. This type of failure could be caused by a broken clock signal cable or a failure of the circuits which drive the clock signal cable. If the DAU sensed the loss of the input timing signal and switched over to the internal master clock, we would have a condition in which the applied input data is varying at one rate and the clock signal generated by the master clock of the DAU is varying at a slightly different rate. The net result would, of course be a loss of bit count integrity. Even if some memory circuit were used in the process of slaving the DAU clock circuits to the input MBS timing, the loss of bit count integrity would merely be deferred until the storage time capability of the memory circuit is expended.

The second type of MBS timing failure is one which causes a loss of both the MBS signal and the associated timing waveform at the input to the DAU. This condition could be the result of a catastrophic failure of the clock circuit associated with the source of the MBS signal (second level multiplexer). If the DAU senses a loss of input MBS timing and switches over to the internal timing mode, the frequency of the transmit timing will be slightly different from that which prevailed before the loss of MBS timing. This follows from the fact that it is highly unlikely that two master oscillator circuits (internal DAU and the MBS source) will exhibit identical frequency accuracy and stability characteristics. It is, therefore, highly probable that a loss of BCI will occur due to the switch-over from one master clock to another, the absence of input data notwithstanding.

The same situation would prevail if a third timing mode was employed; i.e., the derivation of the transmit timing from a station clock which varies at the MBS rate. As with the previously described case, the frequency accuracy and stability of station clock will be different from that exhibited by the internal DAU master clock, and a high probability exists that switching from one to the other will result in a loss of BCI. In general, the probability is relatively high that a loss of BCI will occur in any switch-over from one source of transmit timing to another source.

The only apparent exception to the above described situation is the case in which a switch-over from one MBS timing signal (master input) to the second MBS timing input (slave input) occurs due to a loss of the master input. However, the switch-over from master input to slave input without loss of BCI is predicated on the assumption that both of the timing inputs are of identical frequency and possibly of random relative phase characteristics. The identical frequency requirement presumes that both the master and the slave input timing signals are derived from the same clock source.

Except for the loss of MBS timing signal due to a clock driver failure (second level multiplexer failure) or a broken cable (second level multiplexer-DAU interface failure), interruptions in transmit timing are basically determined by crystal oscillator characteristics. Typical MTBF information on oscillators of the type utilized in the DAU units indicates an MTBF of 400,000 hours. It is not unreasonable to assume that the oscillator utilized in the second level multiplexer and the station clock source are of comparable quality. Therefore, due to the infrequency of oscillator failures, the necessity of being able to switch over in the event of a loss of timing signal from one timing source to another without loss of BCI is subject to question and has not been fully ascertained at this time. Nor has the equity of the exchange of increased system complexity to achieve this operational feature, assuming that it is feasible, been established. However, a cursory examination of several candidate schemes for performing this switch-over function was conducted. It included the utilization of clock averaging techniques and the derivation of the timing signal from the MBS itself rather than the associated MBS timing. No firm conclusions as to the feasibility or cost effectiveness of any of the approaches were formulated as yet.

2.13 DATA SOURCE (SINK)/RADIO SET INTERFACE

The formulation of the data source (sink)/radio set interface characteristics of the DAU equipment was basically a straightforward undertaking with the exception of the specifying of the input/output impedance. Specifically, some degree of uncertainty developed on the advantages and disadvantages of using a balanced input configuration as compared to a simple unbalanced arrangement. The argument for a balanced configuration was predicated primarily on the noise immunity realizable due to the symmetry of the interfacing circuits. This characteristic is particularly beneficial in an environment in which crosstalk due to the presence of many data conducting cables prevails. The relevant advantage of an unbalanced configuration is its compatibility with test equipment such as bit error rate testers, pulse generators, counters, spectrum analyzers, etc.

In light of the developmental nature of the DAU equipment, it was decided that compatibility with test equipment was a more desirable feature for this program than the minimization of crosstalk, especially since it was not clearly evident that in the physical environment in which the DAU will be operated that crosstalk would constitute a problem. Based on these considerations, the DAU equipment was designed to provide an unbalanced input/output for all interfacing digital signals and their associated timing.

The data source (sink)/radio set interfacing characteristics of the DAU equipment are presented below:

DATA SOURCE/DAU INTERFACE

Rate	192 Kbps (1) 3.168 Mbps (1 or 2) 6.336 Mbps (1 or 2) 9.504 Mbps (1 or 2) 12.672 Mbps (1 or 2)
Input Waveform (MBS and SCBS)	Square wave; rise and fall time 10% maximum of baud duration
Input Level (MBS and SCBS)	1 to 5 volts peak-to-peak around ground
Input Signal Format (MBS and SCBS)	Serial binary; NRZ-L
Input Impedance (MBS and SCBS)	75 ohms ±10% unbalanced
Return Loss (MBS and SCBS input ports)	Greater than 20 dB
External Timing Signal Level (supplied by DAU)	2 volts peak-to-peak nominal
External Timing Signal Frequency (supplied by DAU)	192 kHz 3.168 MHz 6.336 MHz 9.504 MHz 12.672 MHz
External Timing Signal Waveform (supplied by DAU)	50 percent duty cycle square wave

External Timing Port Impedance (MBS and SCBS timing)	75 ohms $\pm$10% unbalanced
Return Loss (External timing ports)	Greater than 20 dB

DAU/DATA SINK INTERFACE

Output Rate	192 Kbps (SCBS) 3.168 Mbps (1 or 2) 6.336 Mbps (1 or 2) 9.504 Mbps (1 or 2) 12.672 Mbps (1 or 2)
Data Output Level (MBS and SCBS)	2 volts peak-to-peak nominal across 75 ohm termination
Clock Output Level (MBS and SCBS)	2 volts peak-to-peak nominal across 75 ohm termination
Output Data Format (MBS and SCBS)	Serial binary; NRZ-L
Output Clock Format (MBS and SCBS)	50 percent duty cycle square wave
Output Impedance (Data and timing)	75 ohms $\pm$10% unbalanced
Return Loss (Data and timing output port)	Greater than 20 dB
Connector (Data and timing output)	BNC
Jitter	Peak timing to peak data excursion of less than 5% of data baud interval
Data/Timing Relationship	Positive-to-negative transitions of output timing signal are within $\pm$10% of data baud center

2.14 DAU/RADIO SET INTERFACE

In accordance with the basic design concept, the DAU is required to interface with the transmitter and receiver sections of the FM microwave radio set at baseband. An ideal interfacing arrangement would be

one which resulted in access to the transmitter and receiver sections of the radio being accomplished by means of the normally provided baseband connectors. Unfortunately, the premodulation and post-detection circuits employed in some of the radio sets with which the DAU will operate are not only non-essential to the transmission of digital data but are an impediment to the attainment of a high level of performance. An identification of these circuits for some of the more commonly used microwave radio sets and the reasons for by-passing them are discussed in Section 5.

With the exception of the Aeronutronic Ford LC-4 and LC-8 microwave radio series, the essence of the modifications required of the microwave radios, with which the DAU will operate, is the effecting of an interface at the deviator input and the FM demodulator output. Excluding the effect of the i-f receiver filter, interfacing the DAU at the deviator input and the demodulator output essentially permits all of the microwave radio sets to be characterized by an equivalent if not identical transfer function. If an endeavor is made to standardize the DAU/microwave radio set interface, provisions should be made to have the deviator input and demodulator output signal points of the radio set accessible by means of either front or rear panel located connectors.

The baseband impedance (transmitter input and receiver output) of the Aeronutronic Ford LC-4 and LC-8 type radio sets is nominally 75 ohms unbalanced, as are most of the commonly used radio sets. Since the DAU, as mentioned above, interfaces directly with the normally provided baseband ports of the LC-4 and LC-8 radio sets, it was decided to use the baseband interfacing characteristics of these radio sets to define the baseband interface of the DAU. This decision is not a detriment to the attainment of a satisfactory interface with the other microwave radio sets, since the characteristics of the signal points made available by the modification procedure will be made compatible as part of the modification effort. Based on the above considerations, the DAU/microwave radio set interfacing characteristics are as specified below:

DAU/RADIO TRANSMITTER INTERFACE

Level	1 volt peak-to-peak maximum (adjustable over a 10 dB range)
Impedance	75 ohms $\pm$10% unbalanced
Connector	BNC
Return Loss	Greater than 20 dB

Frequency Response	-3 dB relative to DC response at 1/4 total MBS rate
Waveform	4 level AM

RADIO RECEIVER/DAU INTERFACE

Level	1 volt peak-to-peak nominal
Impedance	75 ohms ±10% unbalanced
Connector	BNC
Return Loss	Greater than 20 dB
Frequency Response	-3 dB relative to DC response at 1/4 total MBS rate
Waveform	4 level AM

SECTION 3

TECHNICAL DESCRIPTION

3.1 SYSTEM DESCRIPTION

Figure 6 is a general block diagram illustrating the multiplexer and redundant modem transmitter interfaced to a redundant analog radio transmitter and the diversity modem receiver and demultiplexer interfaced to a space or frequency diversity analog radio receiver.

3.2 TRANSMITTER

The left-hand portion of Figure 6 excluding the radio transmitter is the DAU transmitter. A description of the DAU transmitter is presented in the following subparagraphs.

3.2.1 Multiplexer

The multiplexer developed for this program is capable of synchronously multiplexing one or two message bit streams and one service channel bit stream. Four switch selectable mission bit stream rates (3.168, 6.336, 9.504 and 12.672 Mbps) can be accommodated by the multiplexer with the switch selectable option of one or two mission bit stream inputs. The service channel bit stream remains fixed at 192 Kbps for any of the aforementioned bit stream input options.

Figure 7 is a block diagram of the multiplexer in which the major functions are highlighted. Referring to Figure 7, it should be noted that the multiplexer provides input mission bit stream timing, service channel bit stream timing as well as modem data timing at any of the previously mentioned mission bit stream rates. The source of all timing signals is either a temperature compensated crystal oscillator that is an integral component of the multiplexer or a switch selectable external timing signal which varies at the mission bit stream rate.

Mission bit stream inputs (one or two depending upon the selected mode of operation) are level translated from bipolar to internal ECL levels by an input data conditioner. In addition, the data conditioner provides for proper sampling of the input data since the timing relationship between the data timing signals and the input data streams as well as the timing relationship of the two input data signals is assumed to be random. After conditioning, the data signals are presented to a randomizer (scrambler). The randomizer serves to facilitate the clock

Figure 6. System Configuration Block Diagram

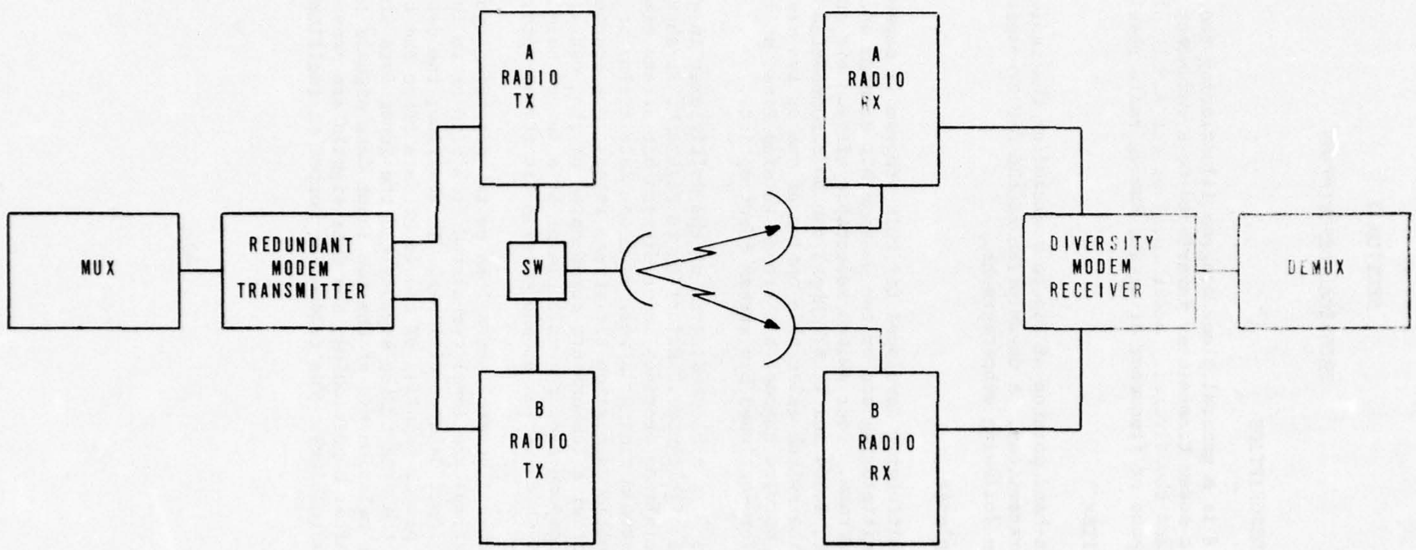
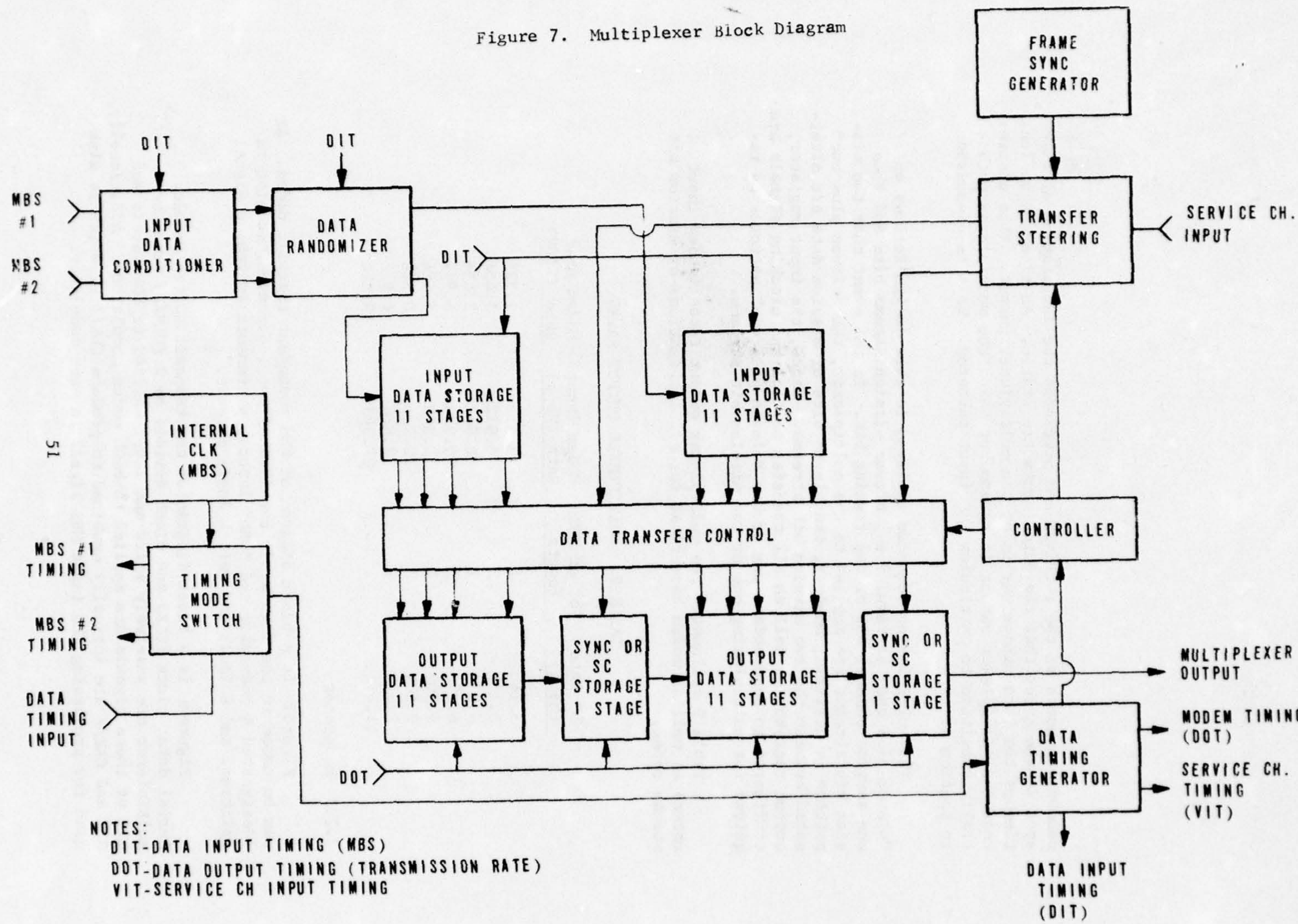


Figure 7. Multiplexer Block Diagram



recovery process at the receiver and precludes the declaration of false sync in the event that the data inputs are static. An alternative location of the data randomizer is at the multiplexer output. This ensures that the multiplexer output is random but makes the multiplexer potentially sensitive to particular MBS input patterns. This is discussed in Section 4.

The multiplexing sequence employed in this design follows an "eleven plus one" pattern; i.e., eleven mission stream bits and then one service channel bit or one framing bit. In the event that two mission bit streams are applied to the multiplexer, the "eleven plus one" pattern is utilized; however, the eleven bits of mission data are alternated between the two mission bit streams. Hence, the input register, output register as well as all transfer control and clocking signals are configured to accommodate one or two "eleven plus one" patterns as required for multiplexing one or two mission bit streams.

Table 9 delineates the multiplexer output rates (modem input rates) as well as modem baud rates for all combinations of mission bit stream rates.

TABLE 9. MULTIPLEXER OUTPUT RATES

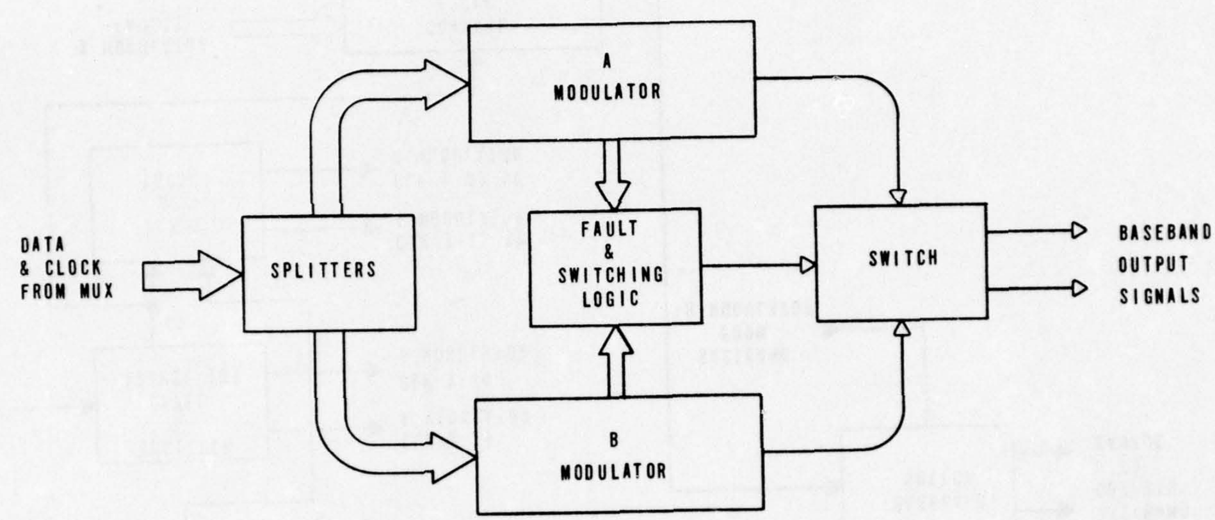
MBS Rate (Mbps)	No. of MBS Inputs	Modem Input Rate (Mbps)	Modem Baud Rate ($X10^6$)
3.168	1	3.456	1.728
3.168	2	6.912	3.456
6.336	1	6.912	3.456
6.336	2	13.824	6.912
9.504	1	10.368	5.184
9.504	2	20.736	10.368
12.672	1	13.824	6.912
12.672	2	27.648	13.824

3.2.2 Modulator

Figure 8 is a block diagram of the redundant transmit modem. As can be noted in the figure, it consists of two independent modulators (designated A Modulator and B Modulator), a transmit switch, a signal splitter, and a fault and switch logic circuit.

Figure 9 is a block diagram of the transmit switch module. Serial data, clock (CLK) and clock divided by 2 (CLK/2) from the multiplexer are passively split and level shifted to ECL levels and all of these signals are applied to both modem modulators. Additionally, CLK and CLK/2 are logically combined to produce CLK/2 Ø2 which is also used for processing the input MBS signal in each modulator.

Figure 8. Redundant Transmit Modem Block Diagram



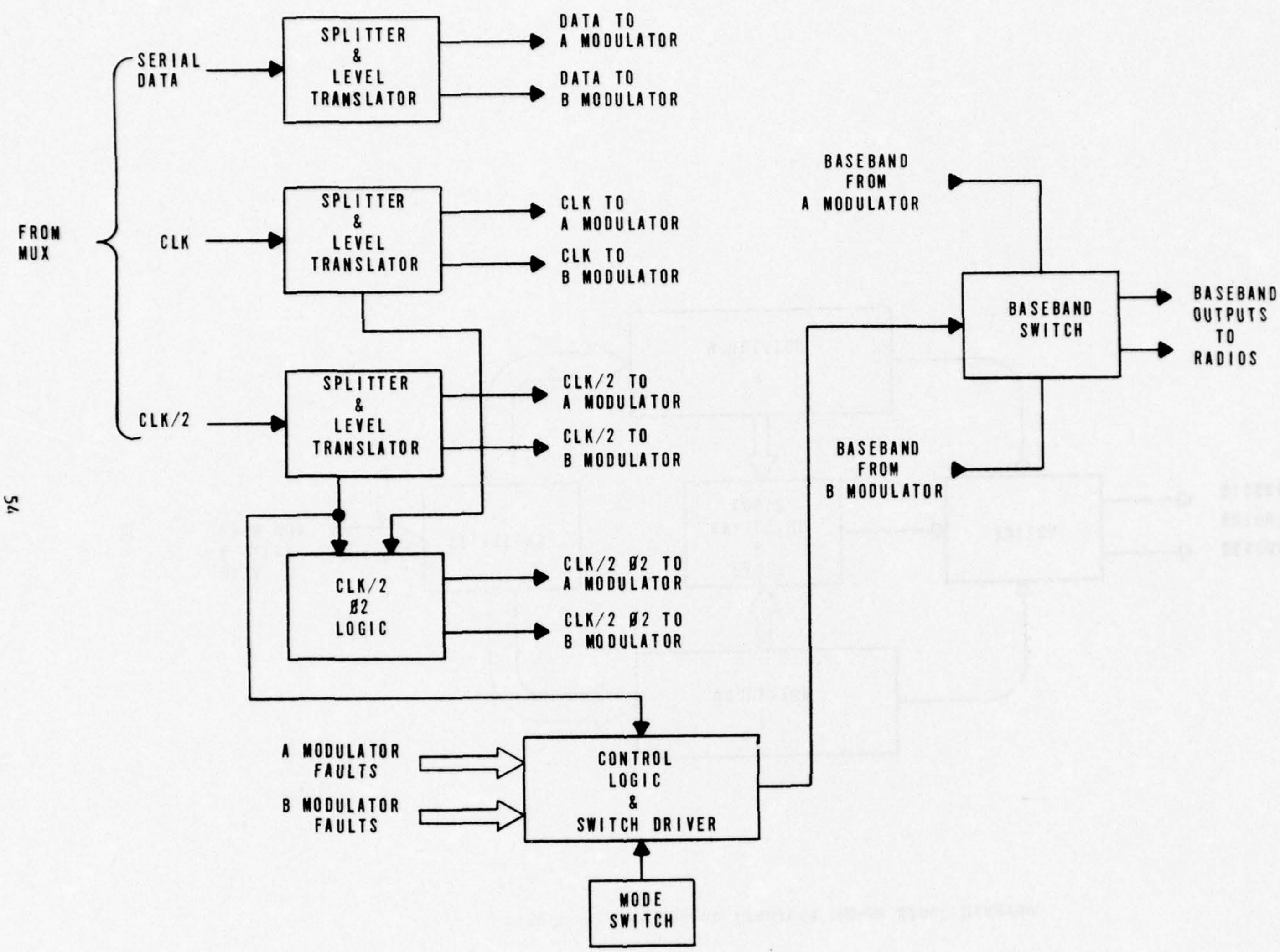


Figure 9. Transmit Switch Module Block Diagram

The transmit switch module contains a pair of junction field effect transistor baseband switches and a passive splitter which serves to place one of the two modulators on-line. The on-line modulator provides two isolated baseband outputs (one output for each of two radio transmitters). Clocked control of the switch is logically accomplished by either a mode switch with two manual positions (A Modulator manually on-line or B Modulator manually on-line) or an automatic mode position where the operational status of each modulator is used to initiate switchover. In the automatic mode, either modulator (A Modulator or B Modulator) may be selected as the on-line unit with the unselected modulator serving as the hot standby unit.

Figure 10 is a block diagram of the transmit modem highlighting the major signal processing functions. Referring to the figure, it will be noted that all timing or clocking signals are derived from the multiplexer via the transmit switch module, except for the local generation of the clock divided by 256 (CLK/256). The latter timing waveform is used solely as the time base for declaring loss of activity at the input and output of the modulator.

The input data is converted to a parallel format and Gray-code encoded, two bits at a time, prior to its application to the 2-bit digital-to-analog converter. After D/A conversion, the data which is in the form of a four-level baseband signal is filtered and amplified in order to offset the amplitude losses experienced in the junction-field effect transistor switch and the passive signal splitter of the transmit switch module.

3.3 RECEIVER

The right-hand portion of Figure 6 exclusive of the two radio receivers is by definition the DAU receiver. A description of the DAU receiver is presented in the following subparagraphs.

3.3.1 Demodulator

Figure 11 is a block diagram of two independent modem receivers and a receive switch configured as a dual diversity receive modem.

Figure 12 is a block diagram of a receive modem (demodulator) depicting the major signal processing and clock recovery functions performed. As can be noted in the figure, the four-level baseband signal after filtering and equalization is presented to four comparators; three of these are associated with data recovery while the fourth comparator provides transition information which is spectrally shaped prior to application to the clock recovery circuits.

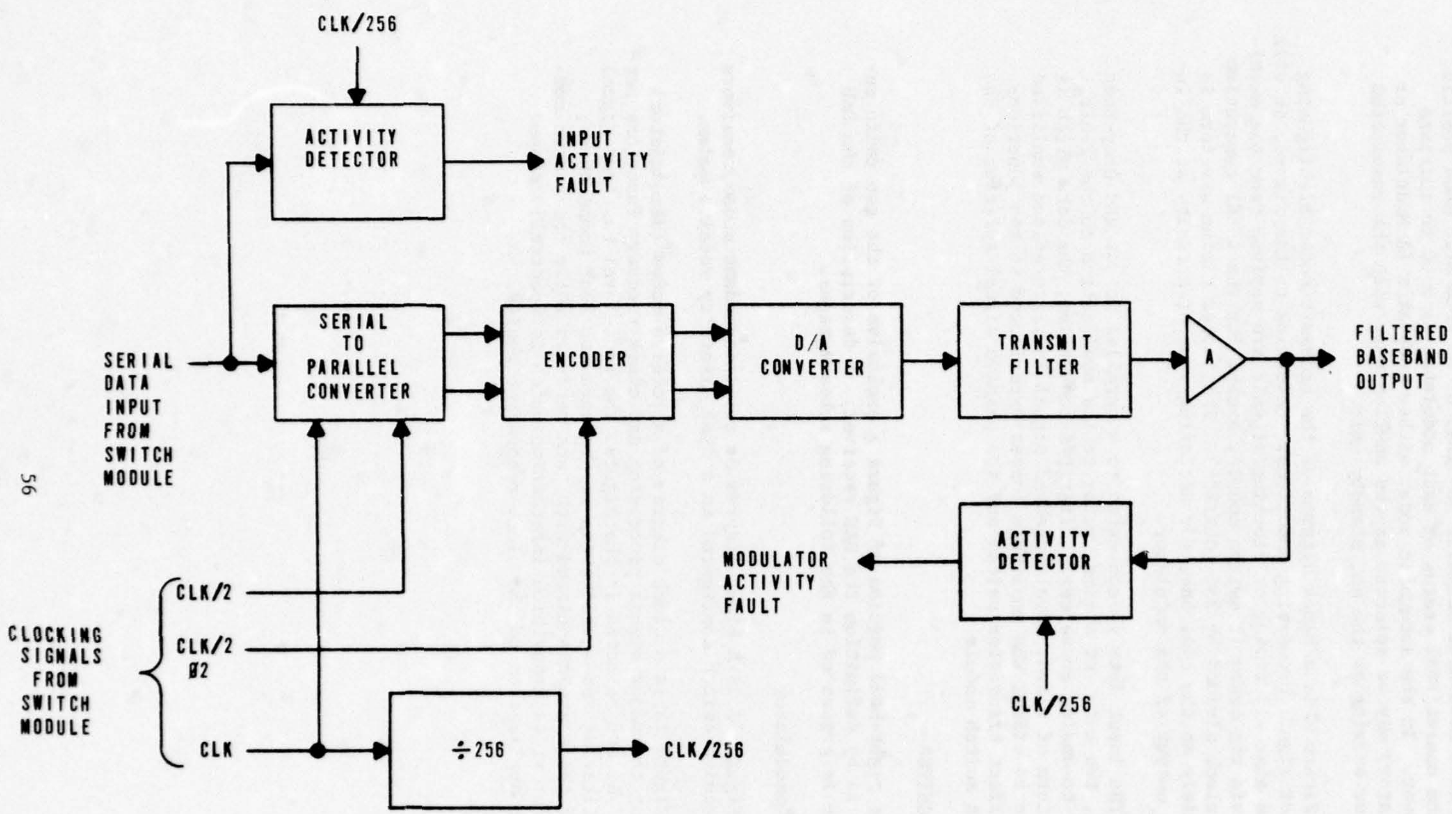


Figure 10. Transmit Modem Block Diagram

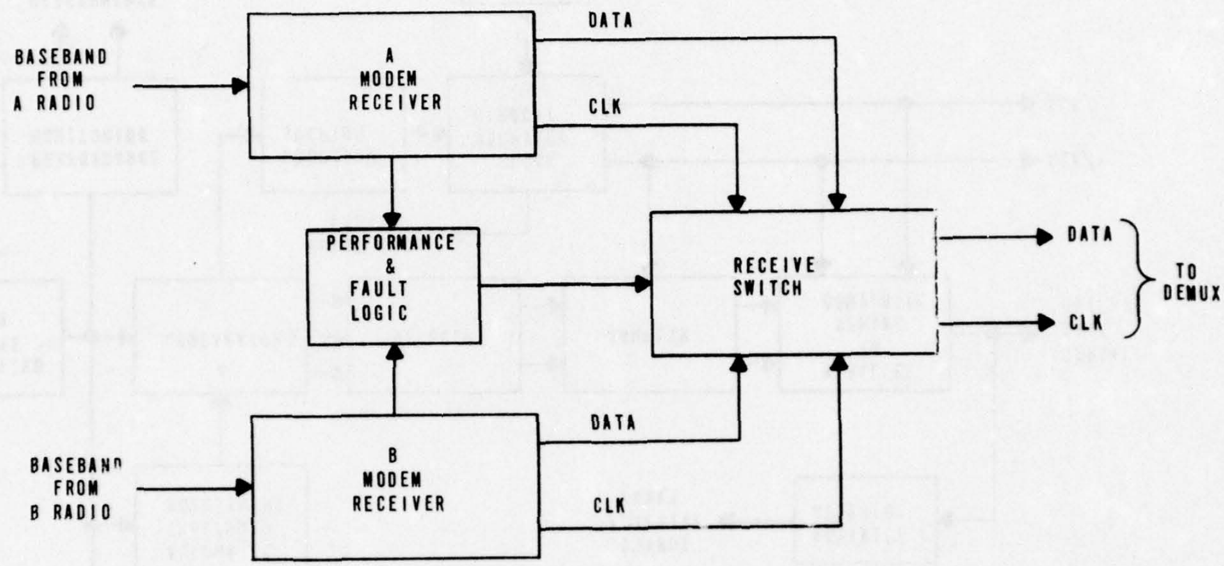


Figure 11. Diversity Receive Modem Block Diagram

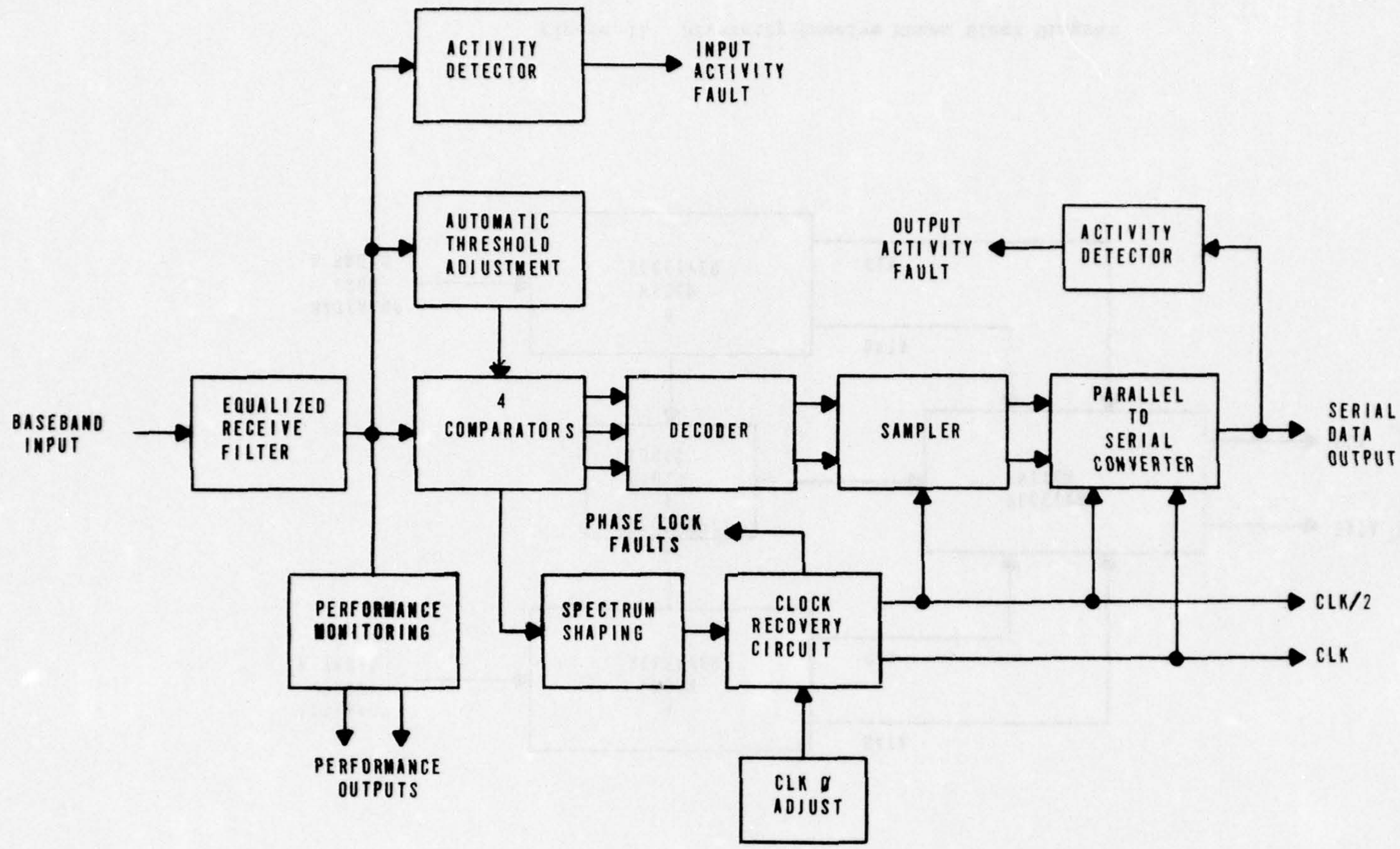


Figure 12. Receive Modem Block Diagram

Multiple rate clock recovery utilizing a single crystal filter preselector is accomplished by translating all clock information to a common IF frequency. The up and down conversion technique incorporates a programmable synthesizer that is controlled by the data rate switch. Clock phasing is implemented as a variable IF delay so that the time range of sampling clock adjustment is greater than the duration of a transmitted baud for all data rates.

The outputs from the three data comparators are decoded and sampled at the baud rate (CLK/2). The retimed data is in a parallel format and must be serialized to obtain a replica of the transmitted data. An activity detector monitors the serial output data stream to provide the performance module and switch module with operational status information for each demodulator.

The filtered four-level input signal is not only processed by the four comparators previously mentioned, but it is also applied to an activity detector, an automatic threshold adjustment circuit and to two performance monitoring circuits. The activity detector provides operational status information while the automatic threshold adjustment circuit compensates the threshold settings for small variations in input signal level. The two performance parameters monitored are out-of-band noise and "eye" closure. Both of these monitors provide an estimate of the operating bit error rate (BER).

The out-of-band noise monitoring circuit develops an analog voltage which is a measure of the system noise falling into a narrow-band crystal filter whose center frequency is selected to be beyond the upper frequency limit of the received data.

"Eye" closure measurement is accomplished by introducing two additional sets of thresholds straddling the data thresholds. If at the sampling time the input signal lies between any set of monitoring thresholds, a current switch is enabled which allows a charge to accumulate on an integrating capacitor until a decision is made at the next sampling time. The analog voltage generated in the monitor circuit is proportional to the log of the accumulated charge on the integrating capacitor.

Figure 13 is a functional block diagram of the performance assessment module. The three voltage comparators determine the relationship of the A radio AGC voltage to the B radio AGC voltage and the relationship of the A demodulator "eye" monitor and noise monitor to the B demodulator "eye" monitor and noise monitor. Adjustable hysteresis and off-set allow each comparator to be set to predetermined switching levels. A mode switch allows each monitor to be selected singly, OR'ed, or as a majority indication.

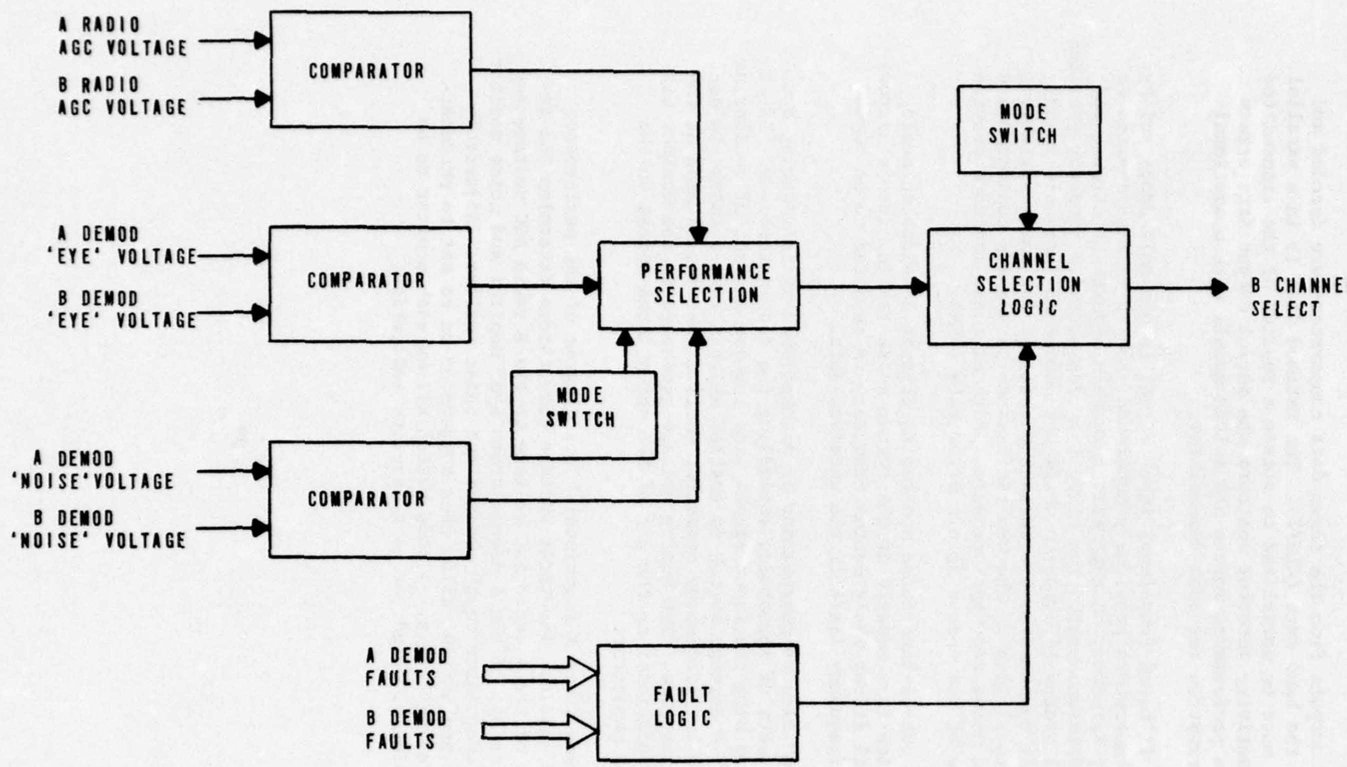


Figure 13. Performance Decision and Switch Control Block Diagram

Although AGC voltage is currently utilized as a performance monitor, analysis of test data clearly indicates that equivalent performance monitoring can be achieved by using only "eye" closure and out-of-band noise signals as the performance criteria. Reliance upon these baseband signal characteristics for performance indication permits the radio DAU interfaces to be reduced to only the baseband signals themselves.

The selected performance signal is logically combined with the operational status of each demodulator to form the B Channel Select signal. Either demodulator may be manually selected to be the on-line unit. However, when the automatic mode of operation is selected, the A demodulator is the on-line unit while the B demodulator serves as a hot standby unit. If the performance monitoring signals indicate that the B demodulator is operating at a higher level of performance, the B demodulator will automatically be selected as the on-line unit until the A demodulator again achieves a superior level of performance, at which time the A demodulator will return to on-line status.

Figure 14 is a block diagram illustrating the major functions performed by the receiver switch. Data and clock signals from both demodulators are presented to selection gates whose control signal is the retimed B Channel Select signal from the performance monitor module. The output of the clock selection gate is applied to a phase locked loop that removes abrupt changes in clock and data phase when switching between demodulators that may exhibit static as well as time variant differential delays of at least $\pm 1/4$ data bit. Retiming of the output data with this clock provides for the smooth slewing of the data when switching under the previously mentioned delay condition. An alternate method of switching the data is to switch the parallel data streams out of the demodulator rather than the serial data stream of the parallel-to-serial conversion. This would increase the allowable differential delay to at least $\pm 1/2$ data bit.

3.3.2 Demultiplexer

Figure 15 is a block diagram depicting the functions required for demultiplexing the received modem signal. Since the multiplexing scheme is based on an "eleven plus one" pattern and since two message bit streams can be transmitted simultaneously, the input register has the capacity to store two "eleven plus one" patterns or 24 stages of storage. Assuming that frame sync has been obtained for the moment, the message bits will occupy register positions 1 through 11 inclusive, and in 13 through 23 inclusive while service channel bits or frame sync bits will occupy positions 12 and 24. The two blocks of eleven bits are each transferred to an output register where they are clocked out at the message bit rate. Bits 12 and 24 are steered either to the frame sync circuits or if they are service channel bits to the service channel output register. In the

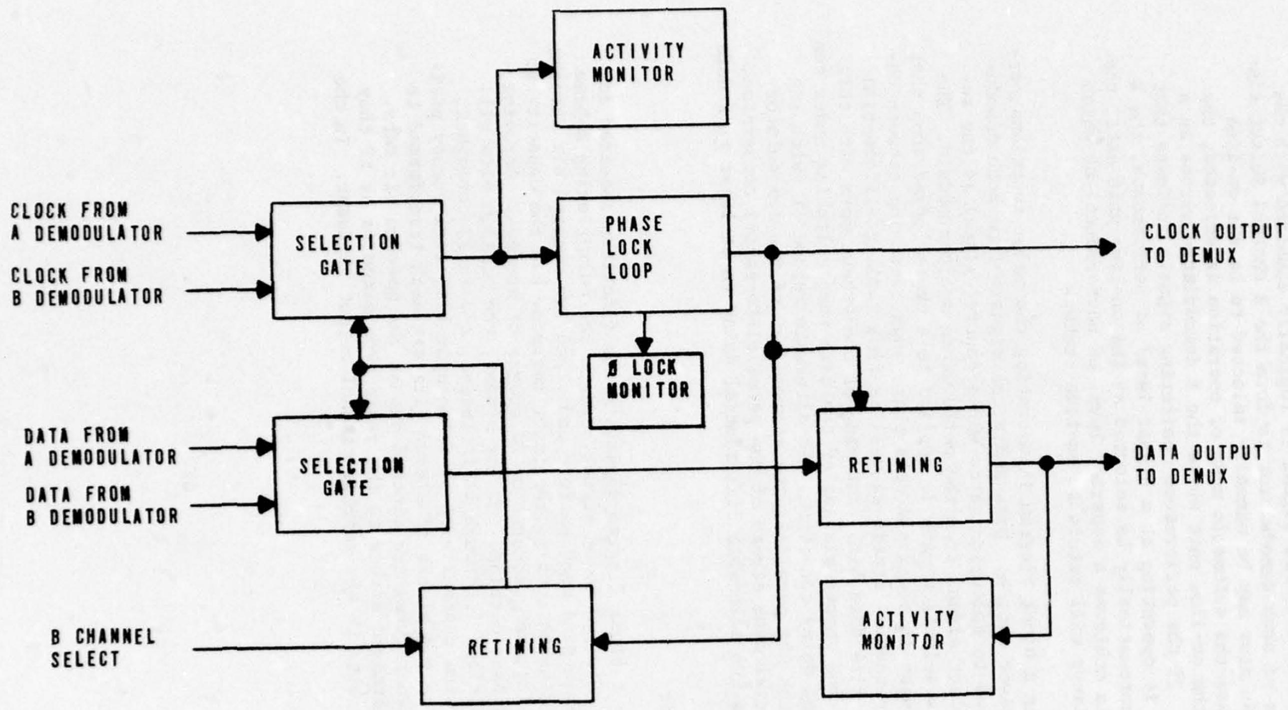
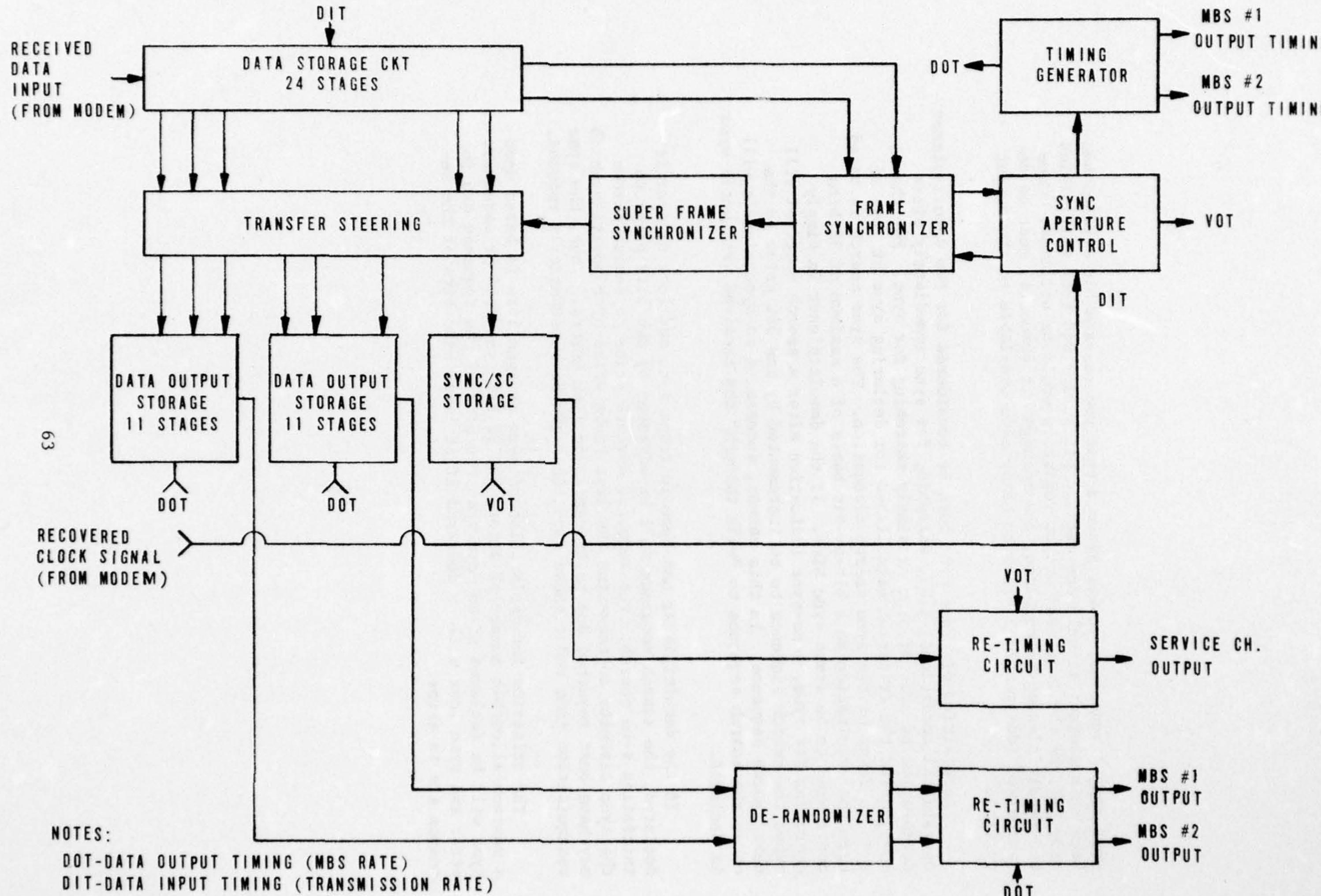


Figure 14. Receive Switch Block Diagram



NOTES:
DOT-DATA OUTPUT TIMING (MBS RATE)
DIT-DATA INPUT TIMING (TRANSMISSION RATE)
VOT-SERVICE CH. OUTPUT TIMING

Figure 15. Demultiplexer Block Diagram

preceding discussion, it was assumed that two message bit streams had been multiplexed; if only one message bit stream had been multiplexed only half of the input and output registers would be utilized. Once the demultiplexing is complete, the message bit stream(s) must be derandomized (descrambled) prior to being made available to the output port(s).

Acquisition of frame sync must be considered for two demultiplexer operational conditions; i.e., searching for sync immediately after declaration of loss of sync or simply searching for sync. For the moment, defer the criterion established for declaring sync or loss of sync in favor of the sync search discussion. The sync search is based upon the examination on a bit-by-bit basis of a maximum of 32 bits considered to be frame sync bits. If the demultiplexer is simply searching for sync, a no-sync indication after a search interval will cause the search sequence to be incremented by one bit prior to the next search sequence. In this manner, successive no-sync signals will cause the search sequence to "walk through" the received data until sync is declared.

If the demultiplexer has been in frame sync and loss of sync is declared, the search sequence will be advanced by two bits prior to initiating sync search. The sequence advance prior to search allows the sync circuits to reexamine the last known valid sync position which may have been rejected due to transmission link errors. Thus, the sync reacquisition time under these conditions can be substantially reduced.

The criterion for declaration of sync or sync loss is based upon a maximum allowable number of errors per 32 bit sync word or sequence. Sync will be declared if no more than two bits of the sequence are in error and sync loss will be declared if at least nine bits of the sequence are in error.

SECTION 4

PERFORMANCE EVALUATION

4.1 INTRODUCTION

The testing of the Digital Applique Unit (DAU) was conducted in five phases. They were:

- Phase 1 - Tests of a non-diversity modem (no MBS-SCBS Mux/Demux) interfaced with the LC-4A, a klystron remodulating terminal, and the LC-4D, a heterodyne terminal, at the Aeronutronic Ford facility. Measurements were made for a single transmission rate of 26.4 Mbps.

- Phase 2 - Tests at Fort Huachuca, Arizona, of a baseband modem interfaced with a Collins AN/FRC-162 and a Motorola MR-300 (AN/FRC-80) radio set. The tests were conducted for the following transmission rates and performance levels[1]: 26.4 Mbps (II), 12.672 Mbps (I and II), and 3.168 Mbps (I).

- Phase 3 - Tests at Aeronutronic Ford using an LC-4A at transmission rates of 26.112 Mbps and 13.056 Mbps. A diversity baseband modem which includes a redundant modulator and errorless baseband switch was used for the tests.

- Phase 4 - Tests at RADC of a diversity baseband modem at a transmission rate of 26.112 Mbps using an LC-8D radio.

- Phase 5 - Tests at RADC of a complete DAU (including MBS-SCBS Mux/Demux). Transmission data rates from 3.456 to 27.648 Mbps were used. (See Table 3).

4.2 PHASE 1 TESTS AT AERONUTRONIC FORD

Phase 1 tests involved a non-diversity baseband modem operating at 26.4 Mbps and an Aeronutronic Ford LC-4D (4 GHz TWT transmitter) radio and an LC-4A (4 GHz klystron transmitter) radio. The test configuration is shown in Figure 16. During this phase, several major objectives

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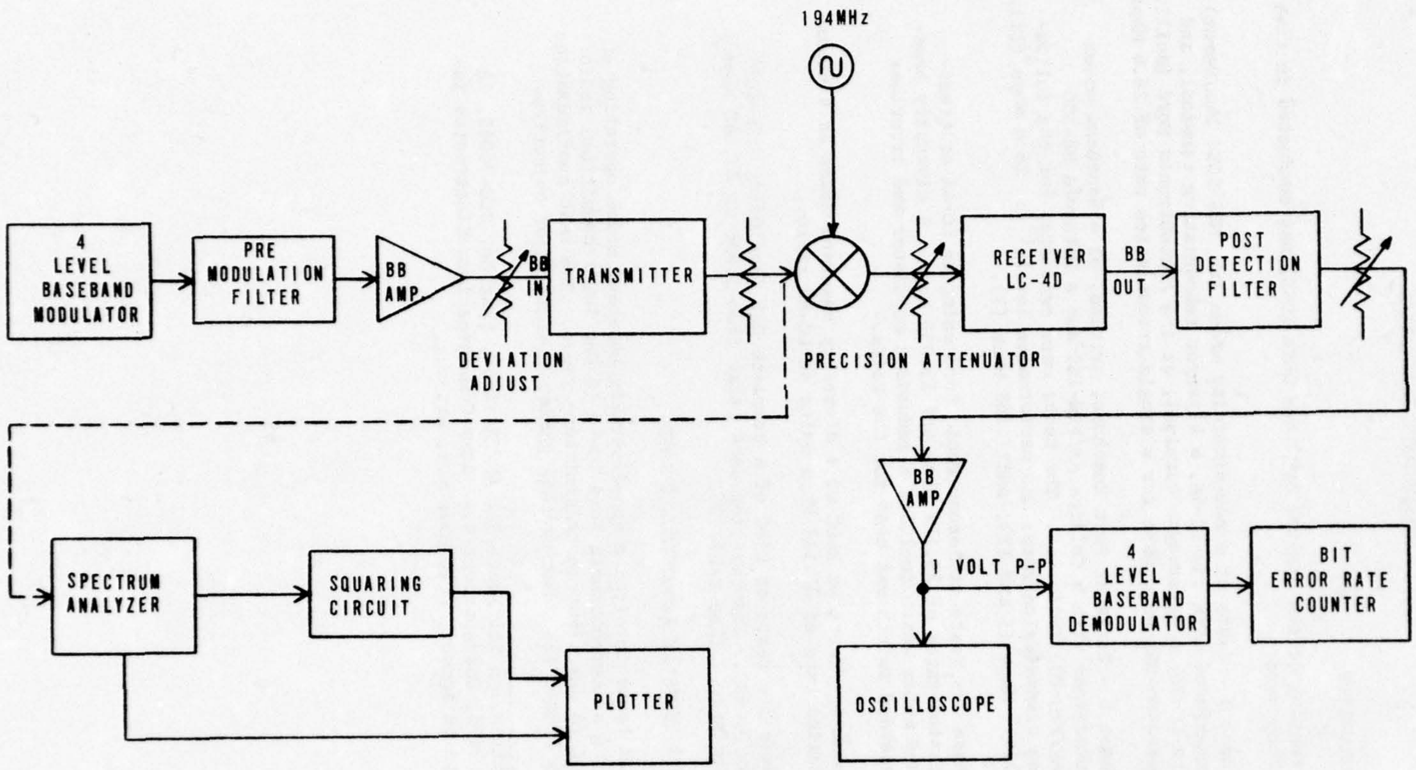
(1) "Specification for Radio Set AN/FRC-163", Spec No. CCC-74049, 22 April 1975, Headquarters U.S. Army Communications-Electronics Installation Agency, Fort Huachuca, Arizona.



BASEBAND MODEM TEST CONFIGURATION
FIGURE 16

were accomplished. These accomplishments are described in the ensuing paragraphs.

Evaluation of alternative modulation schemes including Class I and Class IV partial response and two variations of conventional modulations was performed. The two partial response modulation techniques were empirically evaluated[2] and found inferior to the final version of quaternary modulation at a spectral occupancy of 2 Bps/Hz. The best performance was obtained with a modified form of conventional quaternary modulation which is predicated on achieving a received baseband raised cosine spectrum.

Figure 17 presents the BER vs. C/N performance obtained with Class I and Class IV partial response and the modified quaternary modulation. The E_b/N_0 ratio was measured by introducing a controlled amount of noise at IF using a FKS NG4070R1 generator. A complete discussion of the partial response test results may be found in reference 2.

Figure 18 depicts the BER vs. RSL performance advantage of the raised cosine baseband spectrum technique versus the conventional modulation technique. At a BER of 10^{-7}, there is a 1.3 dB advantage for the raised cosine technique. The advantage of the raised cosine technique is attributable to several factors. First, the optimum filtering for PAM is a received spectrum whose response is -6 dB at the Nyquist frequency[3](transmit and receive -3 dB each). With a conventional modulator the response of the SinX/X baseband spectrum is down 4 dB in the transmitter. Thus, only a post-detection filter whose response is down by 2 dB can be placed in the receiver, which results in an increase in the noise bandwidth and the degradation of the BER. The modified modulator permits responses which are down by 3 dB to be used in both the transmit and receive filters. Finally, the traasmit filter used with the modified modulator limits the baseband spectrum which helps control the spectrum at RF. The combination of transmit and receive filters results in the data having a raised cosine distribution with an alpha of 0.5. The performance penalty in the presence of gaussian noise is approximately 0.4 dB.

Figure 19 shows BER vs. baseband S/N, where the noise is introduced at baseband with a Marconi Noise Generator. The curve shows approximately a .7 dB degradation at a BER of 10^{-7} from the theoretical PAM limit[4]. Figure 20 shows BER vs. RSL and S/N. In this case, the

(2) "Digital Microwave Radio", IR&D Program RG1105, April 1975, B. Olevsky, et al.
(3) "Data Transmission", Bennet and Davey, McGraw-Hill, 1965, Chapter 11.
(4) Ibid.

FIGURE 17
BER VS C/N PERFORMANCE OF BASEBAND MODEMS

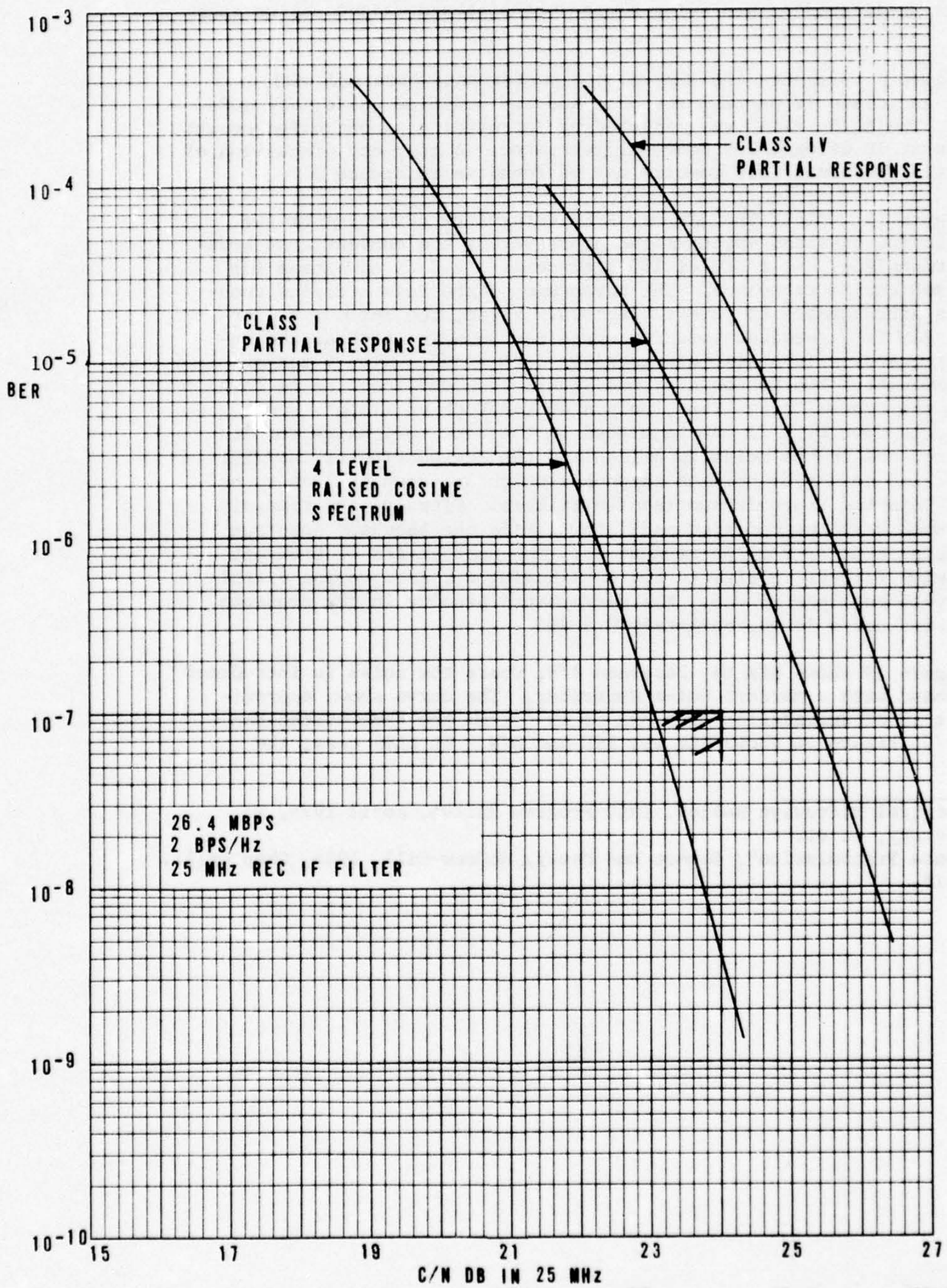


FIGURE 18

BER AS A FUNCTION OF BASEBAND FILTERING

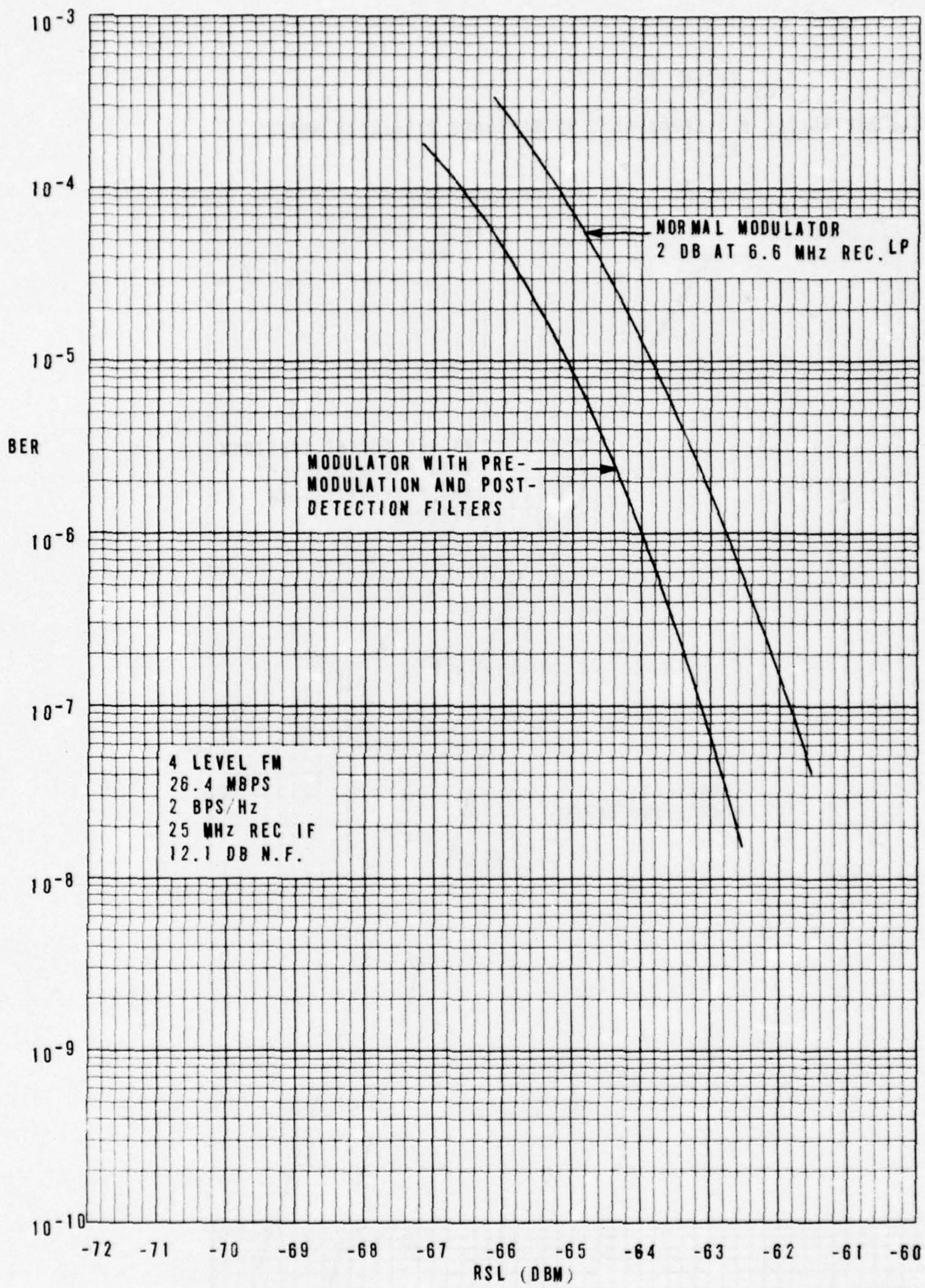


FIGURE 19

THEORETICAL AND ACTUAL BIT ERROR RATE VS BASEBAND SIGNAL TO NOISE RATIO

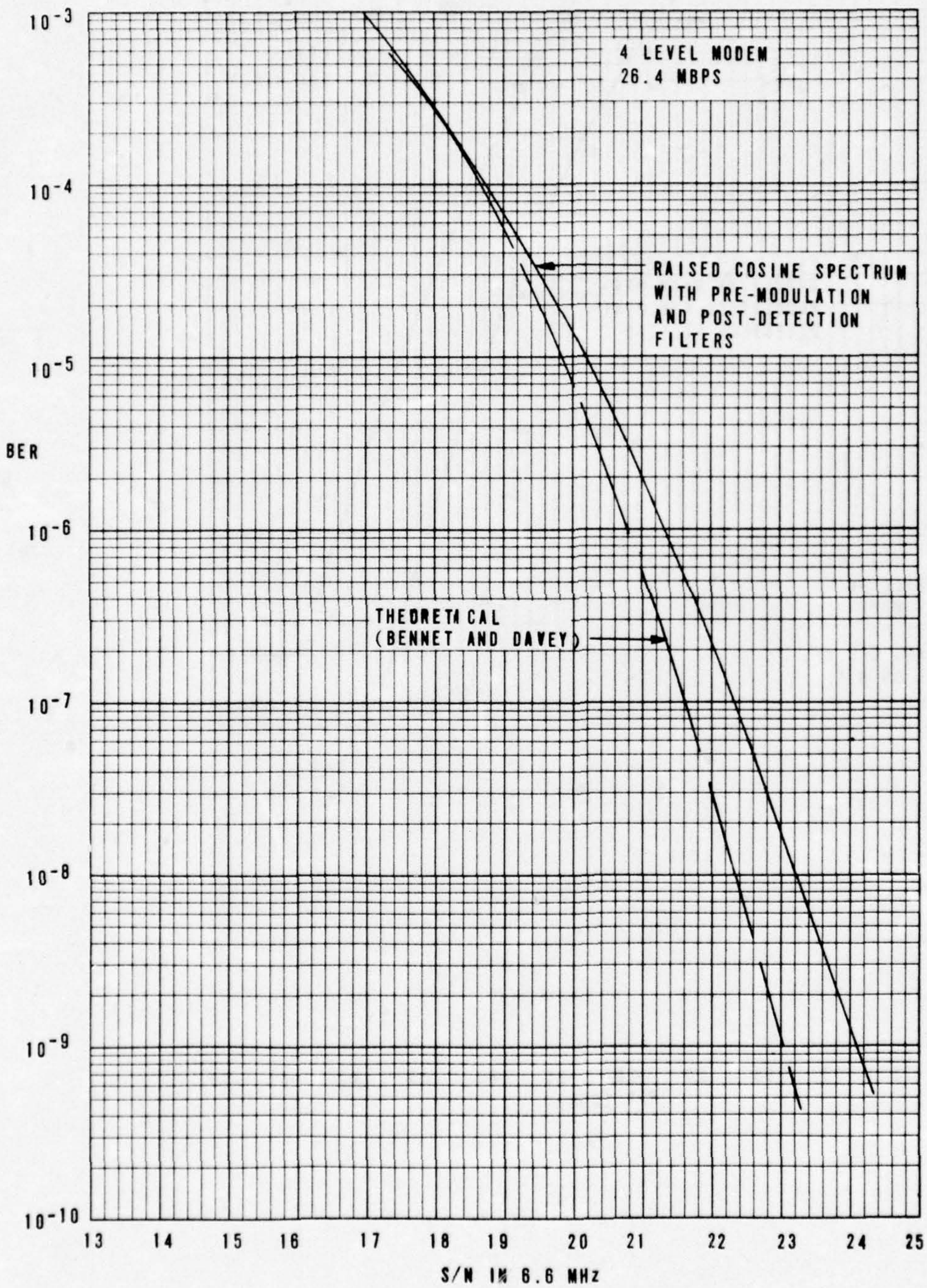
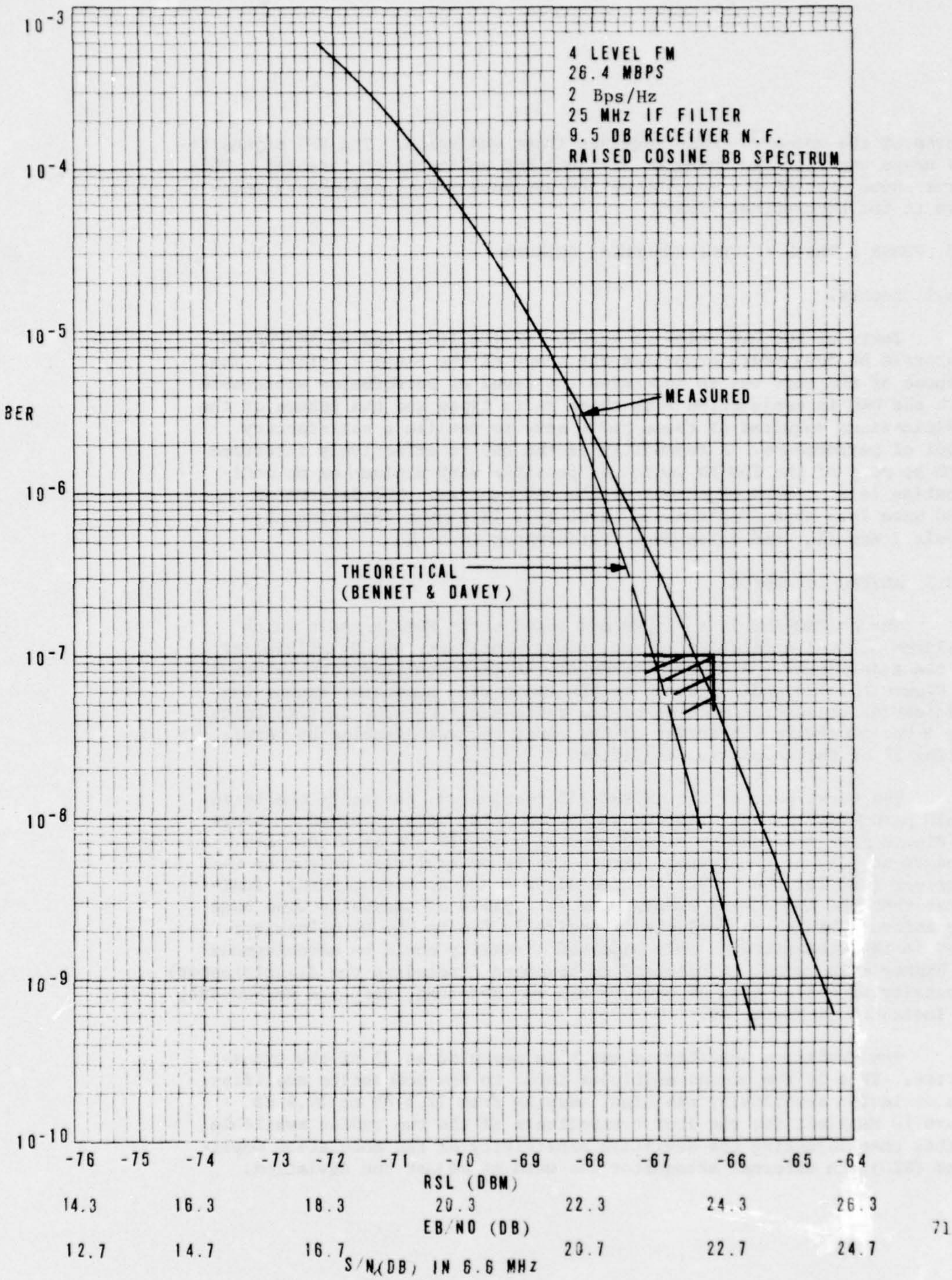


FIGURE 20

LC-4D BER VS. RSL



source of the noise is radio receiver front end noise. The RMS signal to RMS noise was measured using an HP-3400A RMS voltmeter at baseband. This curve shows a .6 dB degradation of the baseband modem performance relative to the theoretical limit.

4.3 PHASE 2 TESTS AT FORT HUACHUCA, ARIZONA

4.3.1 General

Tests of the DAU using an AN/FRC-162 (Collins) and an AN/FRC-80 (Motorola MR-300) radio comprised the scope of the Phase 2 effort. The purpose of the test was to determine the level of performance achievable with the DAU in conjunction with these radio types and the nature of the modifications required of these radio sets to realize a satisfactory level of performance. A capability of the DAU to effectively interface with as many of the FDM/FM radios as possible with minimum or no modification is a primary objective of the DAU program. The data rates used were 26.4 Mbps (Performance Level II), 12.6 Mbps (Performance Levels I and II, and 3.168 Mbps (Performance Level I).

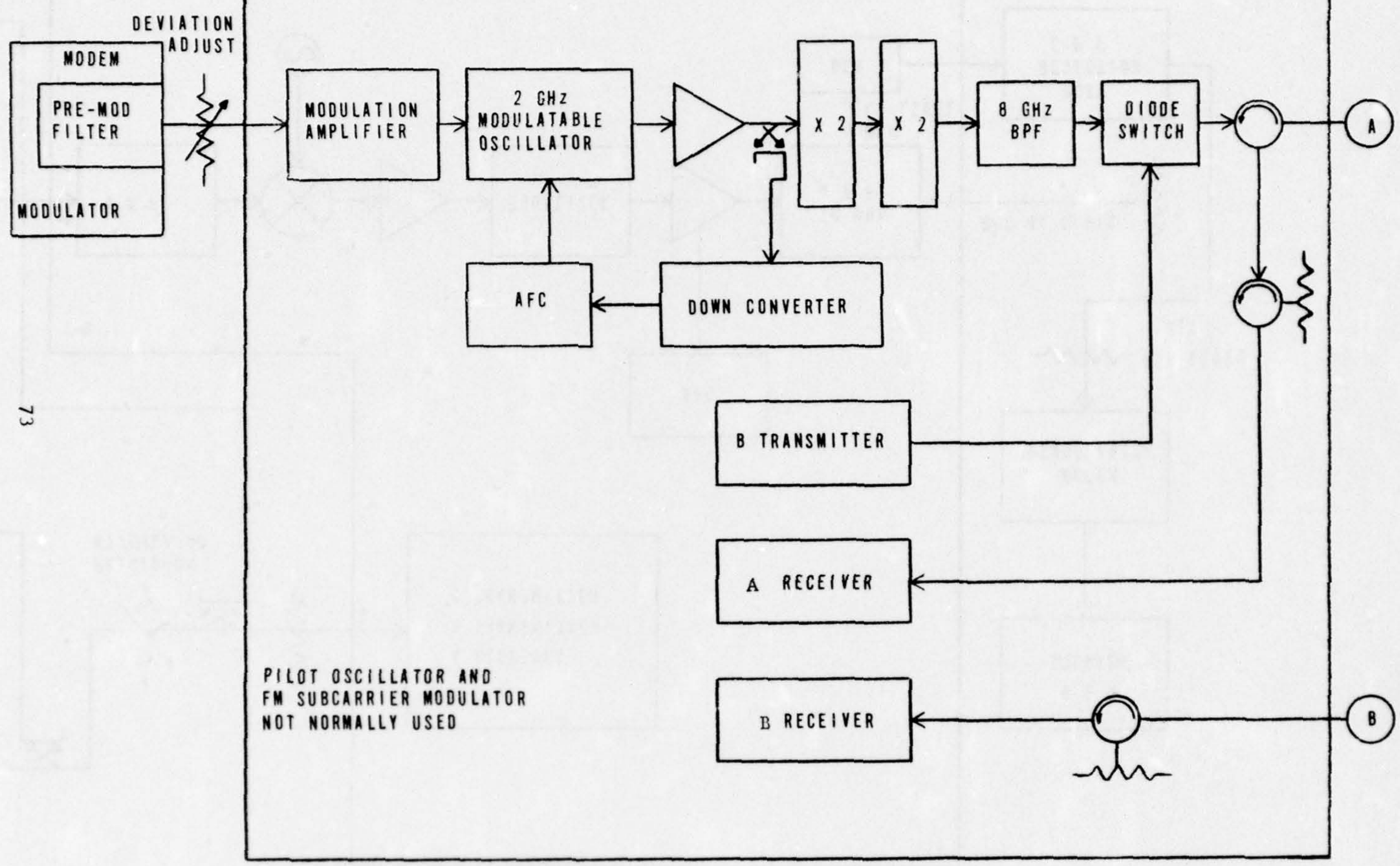
4.3.2 AN/FRC-162 Tests

The AN/FRC-162 is an 8 GHz all solid state FDM/FM radio which utilizes a 2 GHz excitation source, power amplifier, and X4 multiplier in the transmitter. A block diagram of the test configuration is shown in Figure 21. No modifications to the radio were necessary except the elimination of several modules of the radio set. For the initial tests, the 8 MHz orderwire subcarrier of the radio set was disabled by terminating J2 of the modulation amplifier.

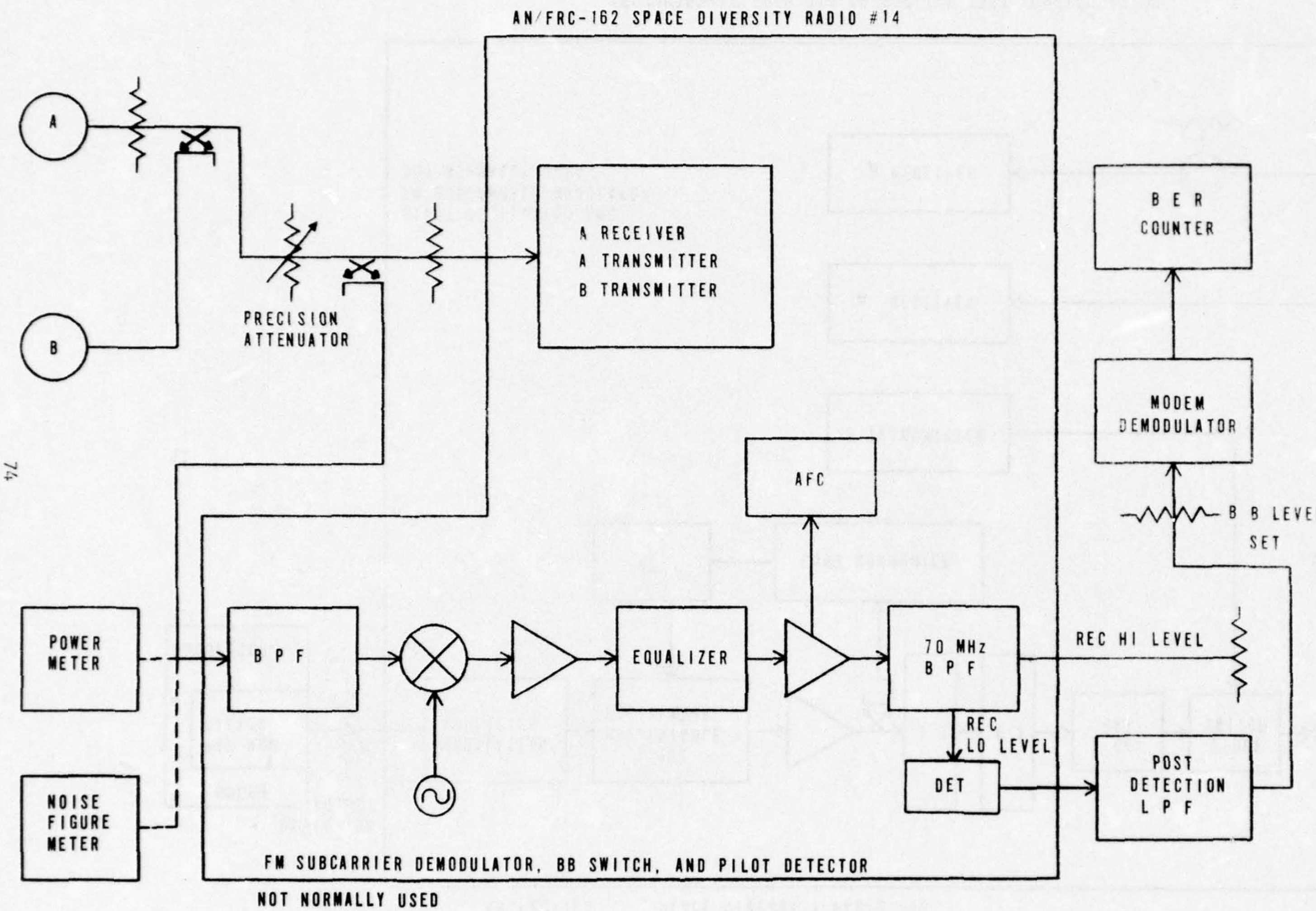
The first part of the AN/FRC-162 testing was to verify the basic radio parameters. The linearity and group delay data obtained is shown in Figure 22. A linearity of 4.5% and 2% over ±10 MHz from the baseband input (J1) of the transmitter to the IF preamplifier output of the receiver (J3) for the transmitter/receiver A and B, respectively, indicates that the AN/FRC-162 transmitter is capable of unusually wide band deviation. This characteristic is basically due to the X4 multiplier used in the transmitter. This wideband linearity could be advantageous at higher data rates. A baseband to baseband (including the discriminator) linearity of better than 3% over ±6 MHz was obtained, with the AN/FRC-162, as indicated in Figure 22.

The deviation sensitivity was then measured at J1 of the transmitter. This is the normal multiplex input to the modulation amplifier. The deviation sensitivity was high, varying from 12.6 dB to 19.4 dB above 10 MHz/volt for the four transmitters of the two radios available. Rather than adjusting the deviation sensitivity of the modulation amplifier (R20), an external attenuator was used to adjust the deviation.

AN/FRC-162 SPACE DIVERSITY RADIO #13



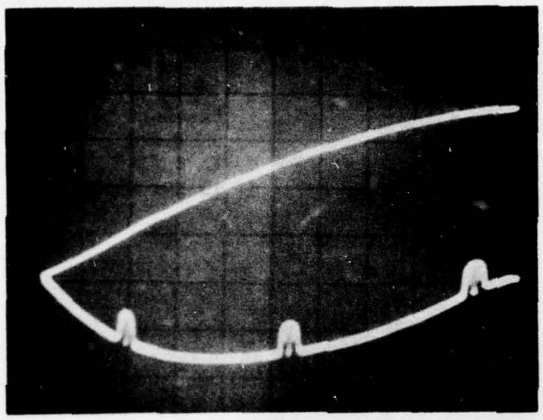
AERONUTRONIC FORD DAU-AN/FRC-162 TEST CONFIGURATION
FIGURE 21-A



AERONUTRONIC FORD DAU-AN/FRC-162 TEST CONFIGURATION

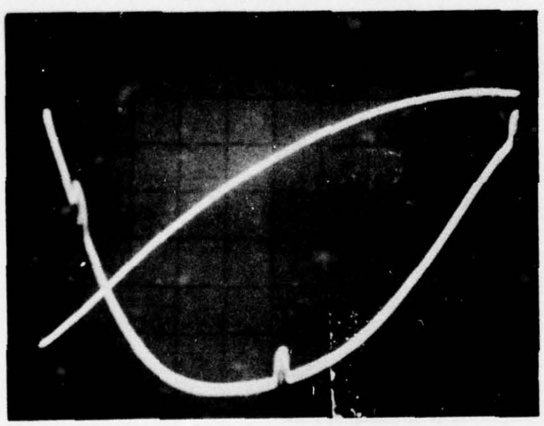
FIGURE 21-B

Figure 22-A
AN/FRC-162 Radio Linearity and Group Delay



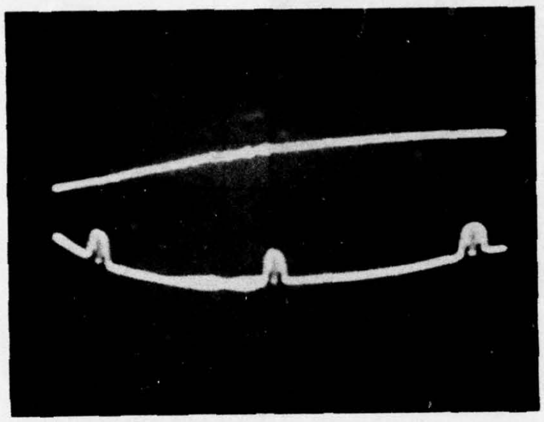
±6 MHz Marker

Baseband to IF
TX A #13
RX A #14
J1 of TX
J3 of Preamp
Upper Trace: 1% per Div.
Lower Trace: 1 nsec/Div.

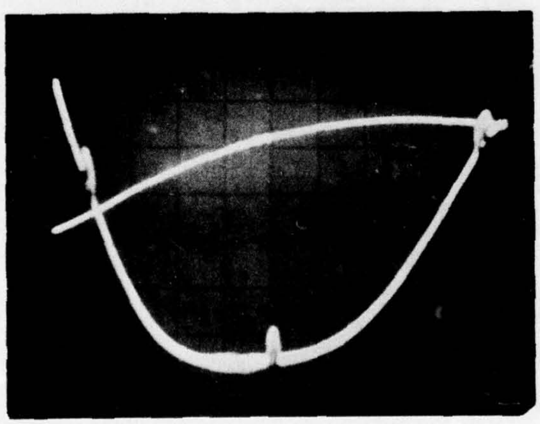


±10 MHz Marker

Figure 22-B
AN/FRC-162 Radio Linearity and Group Delay

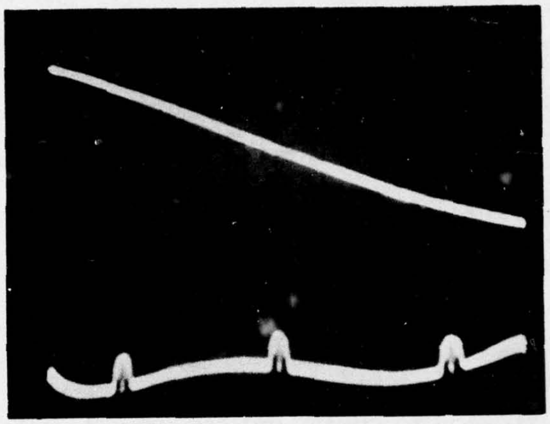


Baseband to IF
TX B #13
RX B #14
±5 MHz Marker

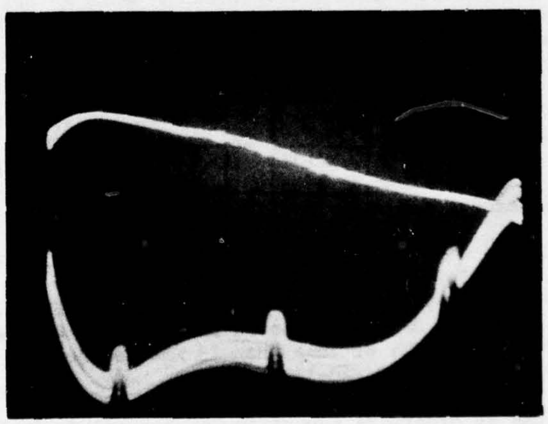


Same as above except ±10 MHz Marker

Figure 22-C
AN/FRC-162 Radio Linearity and Group Delay



Baseband to Baseband
J1 of TX
J59 of RX
TX A #13
RX A #14
1%/Div.



TX 13B
RX 14B
±5 MHz Marker

Once the deviation sensitivity was known, the baseband frequency response of the radio was measured at a peak-to-peak deviation corresponding to 2 Bps/Hz for 26.4 Mbps data. Typically, the baseband response of the radio at 10 Hz, 6.6 MHz, and 10 MHz is down .7 dB, .9 dB and 1.3 dB, respectively, relative to the level at 1 kHz. The baseband of the radio was judged to be compatible with the baseband interfacing requirements of the DAU.

Next, the deviation required to give the desired spectral occupancy at the various data rates was determined. Transmitter B of radio S/N 13 was used for these spectral occupancy and BER tests. The deviations used were as follows:

Transmission Rate (Mbps)	Packing Density (Bps/Hz)	p-p Deviation (MHz)
26.4	2	6.6
12.672	1	6.3
12.672	2	2.8
3.168	1	2.0

Bit error rate vs. received signal level was measured at the aforecited data rates. Plots of BER vs. RSL for 26.4 Mbps (2 Bps/Hz), 12.672 Mbps (1 Bps/Hz and 2 Bps/Hz), and 3.168 Mbps (1 Bps/Hz) are presented in Figures 23 and 24. For 3.168 Mbps, the squelch was disabled by grounding the squelch test point 22E4C-MW, because it became active at too low an RSL for the lowest data rate. Since the baseband squelch is not required with a diversity modem, it normally would be disabled. Hence, the disabling of the squelch circuit for the test did not constitute an abnormal operating condition.

The interface points on the AN/FRC-162 were J1 of the radio jack panel (modulation amplifier input) and J59 of the radio jack panel (receiver BB output). Because the AN/FRC-162 receiver baseband output is DC coupled and has a DC component of +1.7 volts, a coupling capacitor was added to the modem demodulator input for interfacing purposes.

The BER measurements were all made with the available AN/FRC-162 receiver 25 MHz IF filter. This filter is excessively wide for the lower data rates (especially 3.168 Mbps) and as a consequence some BER vs. RSL measurements were made with the RSL below the FM threshold of the radio. A family of filters with bandwidths of less than 25 MHz and down to a bandwidth of 7 MHz exists for the AN/FRC-162.

The AN/FRC-162 has an orderwire subcarrier at approximately 8 MHz and a pilot at approximately 9 MHz. The preceding BER measurements were made with the orderwire and pilot removed by terminating the input

FIGURE 23

BIT ERROR RATE VS. RECEIVED SIGNAL LEVEL

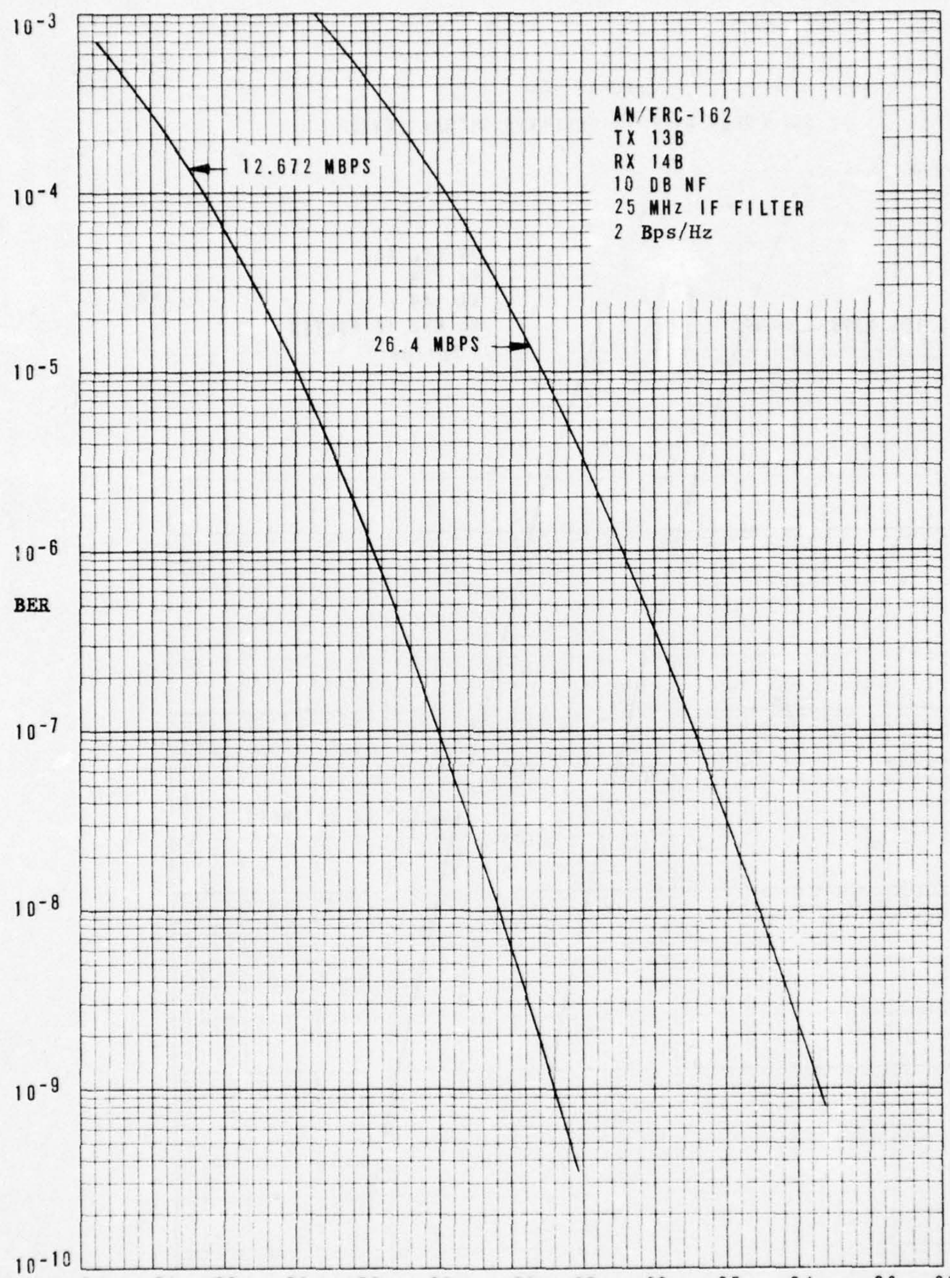
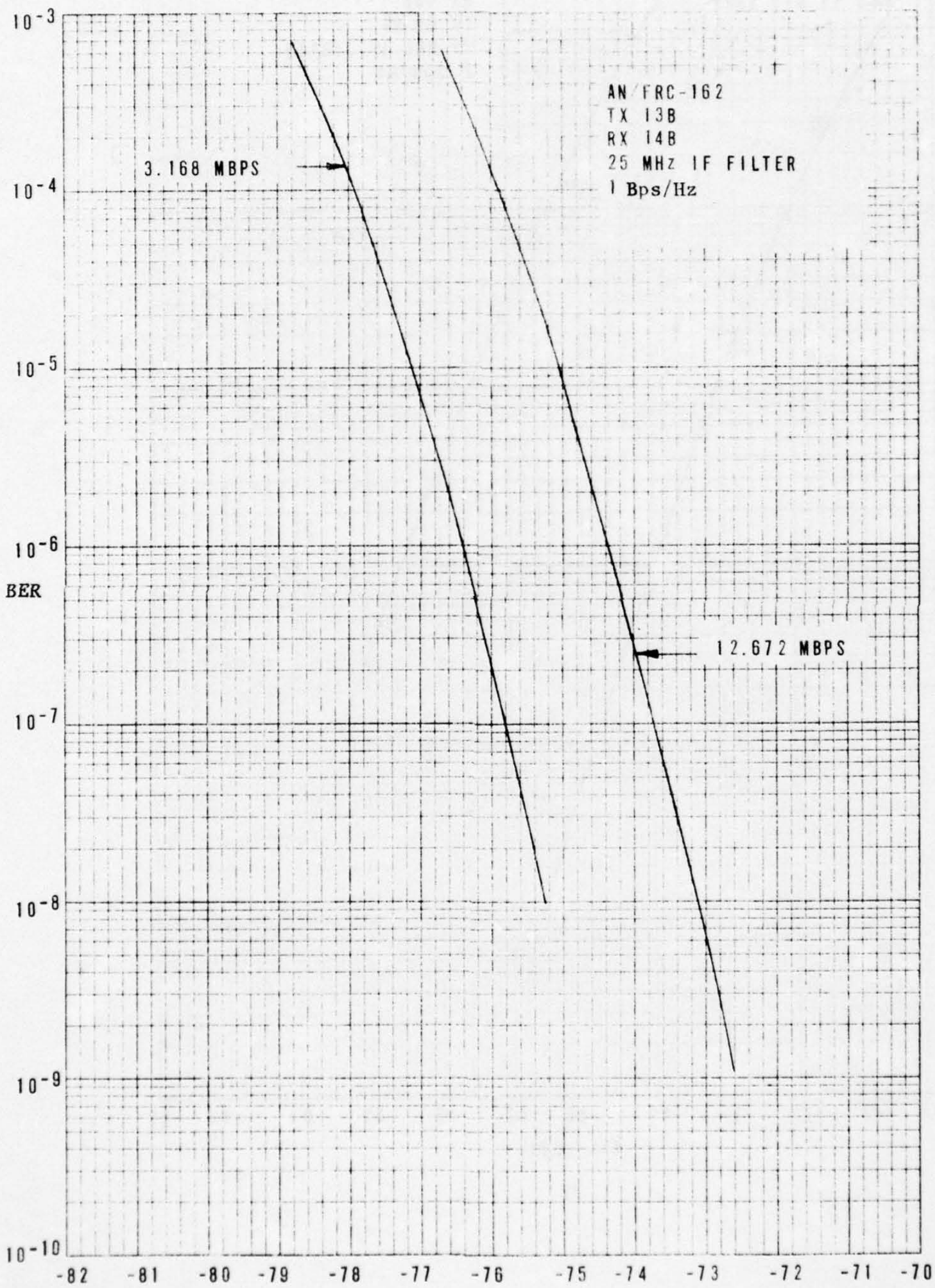


FIGURE 24

BIT ERROR RATE VS RECEIVED SIGNAL LEVEL



to the transmitter modulation amplifier (J2). To determine the effects of the orderwire and pilot on BER, measurements were made with and without the orderwire and pilot. At 12.672 Mbps (1 Bps/Hz and 2 Bps/Hz), the presence of the pilot made no measurable difference in BER vs. RSL. The unmodulated orderwire degraded the BER vs. RSL characteristics by about 0.5 dB. The level of the unmodulated orderwire was 26 dB below the carrier, and the pilot was 37 dB below the carrier.

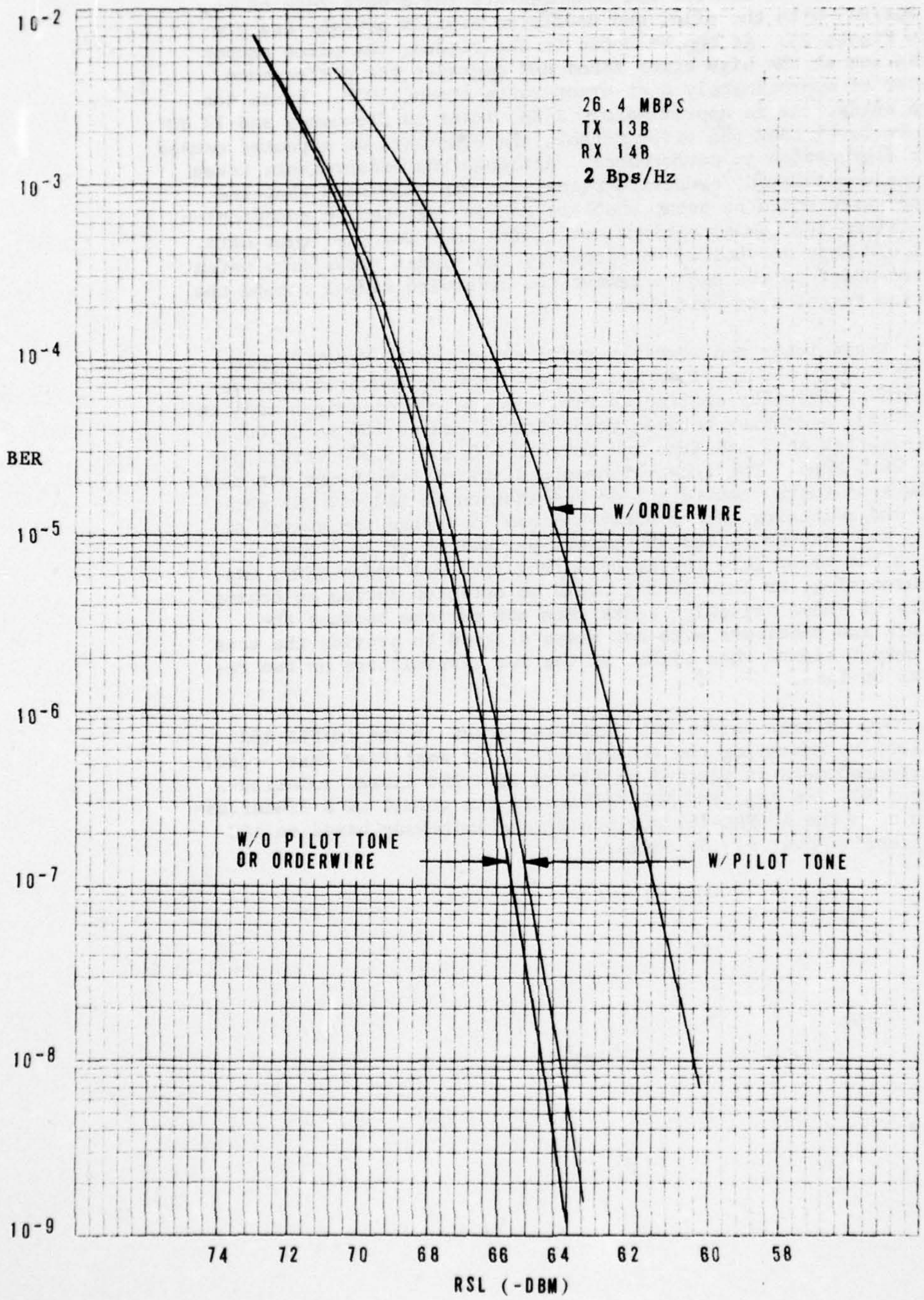
The results of BER vs. RSL measurements for a data rate of 26.4 Mbps (2 Bps/Hz) with the pilot and orderwire signals present are presented in Figure 25. As can be noted in the figure, the pilot causes no degradation at the high error rates and degrades the performance by a factor of approximately 2 at error rates around 10^{-8}. Since the orderwire subcarrier is approximately 1 MHz lower in frequency and 11 dB stronger in level than the pilot signal, the orderwire as expected caused a greater degradation in performance. Although the measurements taken were for an unmodulated, orderwire signal, it was concluded that the analog orderwire could be used, when the DAU is operated in conjunction with the AN/FRC-162, as an optional orderwire mode for the lower data rates (12.672 Mbps and below) and possibly the higher rates if a notch filter were added to the DAU to remove the orderwire signal before the demodulation function is performed.

The transmitter and receiver switches of the AN/FRC-162 were tested even though the receiver switch would not be required when operating with a diversity configured DAU. In the manual switch mode on the AN/FRC-162, switching between transmitters caused 100 to 30,000 errors per switch at 3.168 Mbps and between 450 and 55,000 errors per switch at 26.4 Mbps. The receiver baseband switch (which was not used in the previous tests) caused a 1 dB degradation in BER vs. RSL performance, and switching caused between 3 and 15 errors per switch at 3.168 Mbps and between 30 and 900 errors per switch at 26.4 Mbps. Because the bit error rate tester used (the internal modem BERT) was self-synchronizing, no loss of BCI could be detected during switching. The results of these switching tests were not optimum because the transmitters and receivers were not phase aligned to provide the same baseband output signal when either of the two transmitters or two receivers was on line.

The AGC voltage versus RSL characteristics of the AN/FRC-162 were obtained by measuring the voltage of the IF amplifier test point, and the procured data is plotted in Figure 26. The linear relationship between RSL (in dBm) and AGC voltage is the result of a linearization circuit in the AN/FRC-162 and would make switching based on AGC voltage effective over a wide range.

FIGURE 25

PERFORMANCE DEDRADATION DUE TO PILOT TONE AND ORDERWIRE FOR AN/FRC-162 RADIO



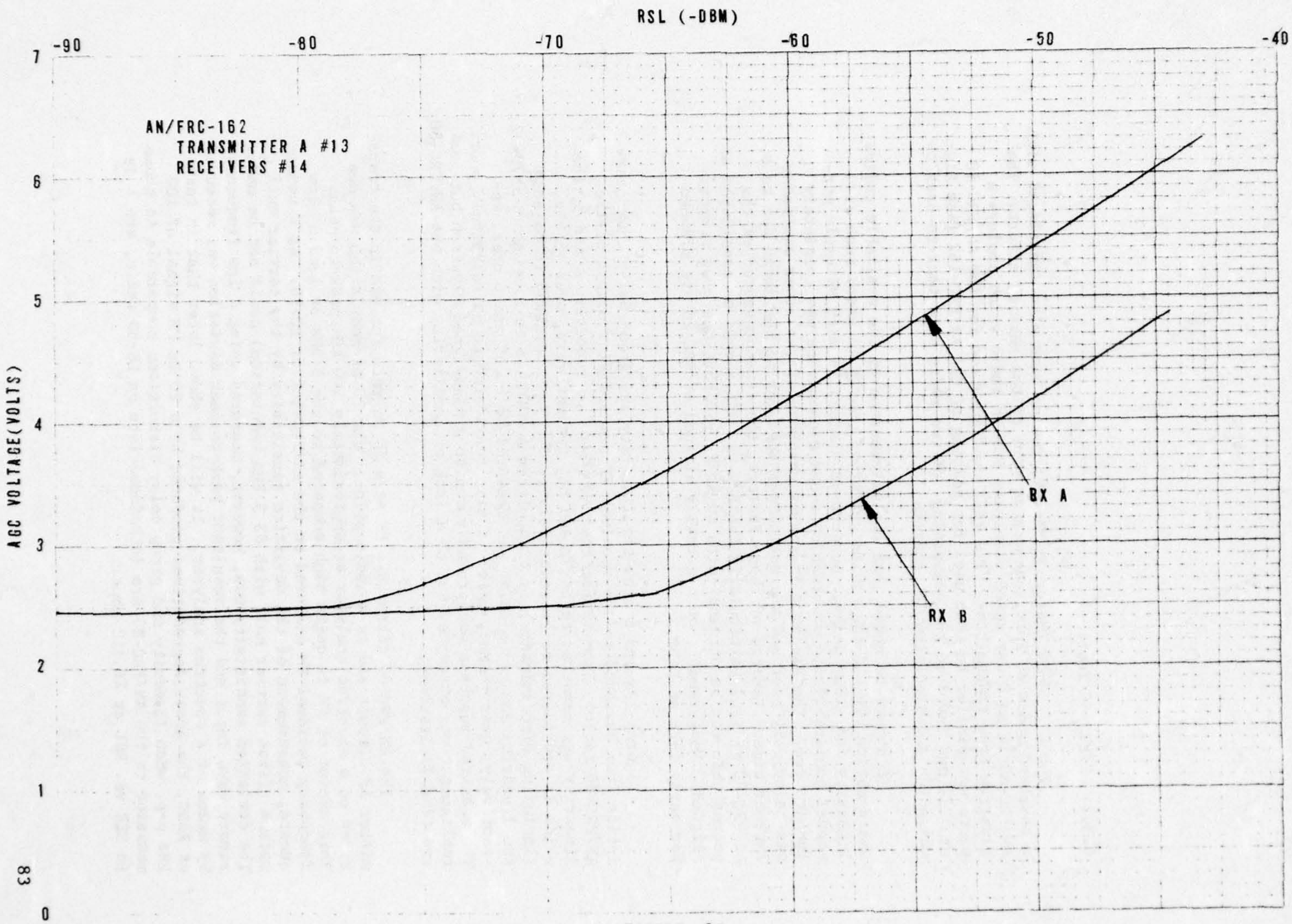


FIGURE 26
AGC VOLTAGE VS RSL

4.3.3 AN/FRC-80 Tests

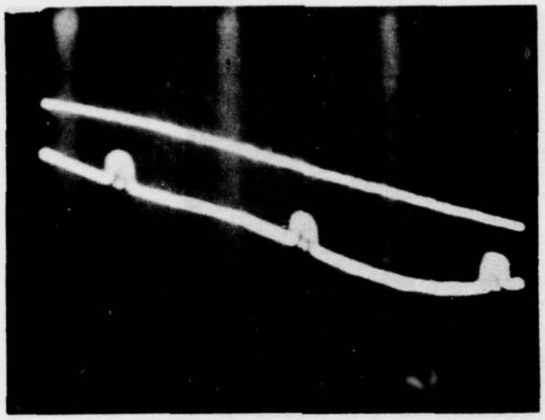
Two AN/FRC-80 (Motorola MR-300) radios were also interfaced with a baseband modem at Fort Huachuca as part of the testing effort. The AN/FRC-80 is an 8 GHz space diversity FDM/FM radio which employs a klystron type transmitter. The test configuration for the AN/FRC-80 tests was similar to that used for testing of the AN/FRC-162 (see Figure 21) and involved the connecting of two radio sets back-to-back by waveguide and precision attenuators.

It should be noted that the maintenance of the available radios was questionable and the radios performed poorly in areas such as linearity and group delay. Subsequent discussion with Motorola personnel confirmed this observation. One transmitter was completely inoperative. The baseband frequency response of the other equipment was relatively poor and was not compensated for in the modem due to a lack of time. Because of these factors, the data presented on the AN/FRC-80 radios, particularly the BER vs. RSL, should be considered as poorer than can be obtained with an AN/FRC-80 that has been properly aligned. Measurements on a normally aligned AN/FRC-80 are planned for early 1976 at RADC.

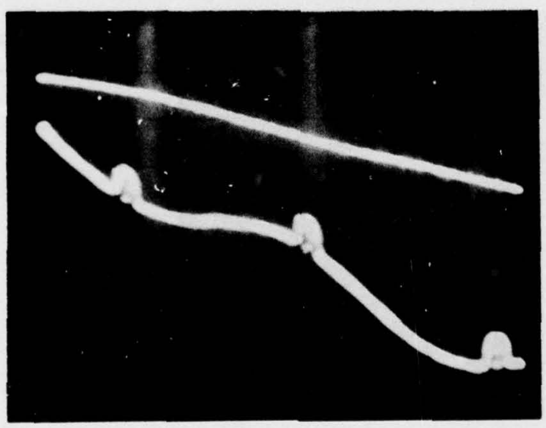
Figures 27a and b show the linearity and group delay characteristics from baseband to the receiver IF preamplifier output of the AN/FRC-80 radio. From transmitter A SN78445 to receivers A and B, the linearity was measured to be 7% and 6%, respectively, over ± 5 MHz, which is considered to be relatively poor. From baseband to baseband (including discriminator) of transmitter A SN78445 to receiver B SN78432, the linearity and group delay was measured to be 6% and 6 nsec, respectively, over ± 5 MHz, which is also considered to be relatively poor. The measured response was probably due to a misaligned klystron but no realignment was attempted due to a lack of familiarity with the AN/FRC-80 and time limitations.

The AN/FRC-80 introduces FM at a 20 Hz rate for use in the transmitter AF circuit and as a radio pilot. The 20 Hz modulation was measured on a spectrum analyzer as approximately 100 kHz peak-to-peak. This amount of FM is quite high compared to the 5 kHz or less of low frequency residual FM measured on the AN/FRC-162 or LC-8D. As a consequence, measurement of the deviation sensitivity by the carrier null method (first carrier null with 83.3 kHz modulation) could not be made. The deviation sensitivity was, however, measured using a low frequency square wave input and the resultant peak-to-peak deviation was measured by means of a spectrum analyzer. It will be shown later that in tests at RADC, the gross degradations produced by a 20 Hz FM signal of 100 kHz p-p, when linearity and group delay distortions comparable to those measured on the AN/FRC-80 are introduced into an LC-8D radio, are 1 dB in BER vs. RSL at 26.112 Mbps.

Figure 27-A
AN/FRC-80 Radio Linearity and Group Delay

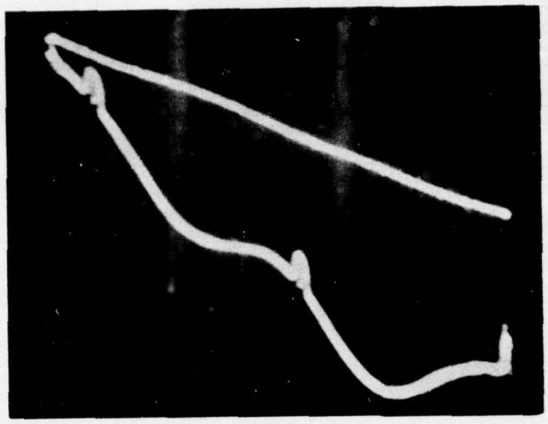


Baseband to IF
TX A SN78445
RX A SN78432
5 MHz Marker
3%/Div.
3 nsec/Div.

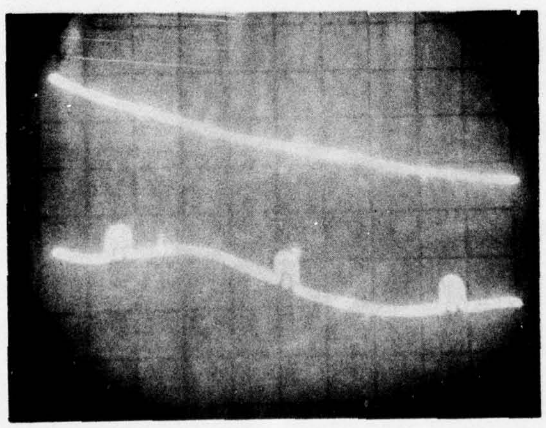


TX A SN78445
RX B SN78432

Figure 27-B
AN/FRC-80 Radio Linearity and Group Delay



±9 MHz Marker
TX A SN78445
RX B SN78432



Baseband to Baseband
TX A SN78445
RX B SN78432

The spectral occupancy of the data modulated RF signal was measured at 26.4 Mbps (2 Bps/Hz) and 12.672 Mbps (1 Bps/Hz and 2 Bps/Hz). To obtain a given Performance Level, essentially the same peak-to-peak deviation was required for the LC-4D, LC-4A, AN/FRC-162 and AN/FRC-80 radios.

BER vs. RSL for the above data rates and performance levels was then measured using the AN/FRC-80 radio set. The results obtained are presented in Figures 28, 29 and 30 . As can be noted in the figures, the performance of the AN/FRC-80 is 3.5 dB and 1.7 dB worse than the AN/FRC-162 at 26.4 Mbps and 12.672 Mbps (1 Bps/Hz), respectively, which includes the effect of the difference in radio set noise figures. A part of the performance difference is attributable to the residual FM, baseband nonlinearity, and group delay of the AN/FRC-80 radio set as was mentioned previously. However, the bulk of the performance degradation is attributed to the baseband frequency response of the AN/FRC-80 radio.

The measured baseband-to-baseband frequency response of the AN/FRC-80 is shown in Figure 31. Referring to the figure, it can be noted that at the Nyquist frequency for the 26.4 Mbps data rate case (6.6 MHz), the baseband response is down from the desired 0 dB value. This condition can be compensated for by adjusting the low pass filter of the baseband modem demodulator to be less than -3 dB at the Nyquist frequency. The penalty in BER vs. RSL due to the increased noise bandwidth resulting from the retuning of the baseband filter should be considerably less than the penalty due to eye closure (intersymbol interference) caused by incorrect baseband response.

For the BER vs. RSL tests, a 20 Hz notch filter was used in the baseband modem demodulator input to remove the 20 Hz AFC signal used in the AN/FRC-80. However, this filter made little difference in the error rate results and may not be a necessary radio modification.

The AGC vs. RSL voltage on the AN/FRC-80 was measured. The results are shown in Figure 32. Because of the limited RSL range over which the AN/FRC-80 AGC voltage is linear, the switching based on AGC may be less effective on the AN/FRC-80 than other radios, especially at the high signal level case.

4.4 PHASE 3 TESTS AT AERONUTRONIC FORD

4.4.1 Test Results

Tests were performed at the Aeronutronic Ford laboratory on the diversity modem operating with the LC-4A radio at data rates of 26.112 Mbps and 13.056 Mbps. The diversity modem consisted of a redundant transmitter and diversity receiver and the performance assessment circuits. Performance assessment was based upon receiver AGC, out-of-band noise, and received eye closure.

FIGURE 28

BER VS RSL FOR DAU MODEM WITH MOTOROLA AN/FRC-80 MICROWAVE RADIO

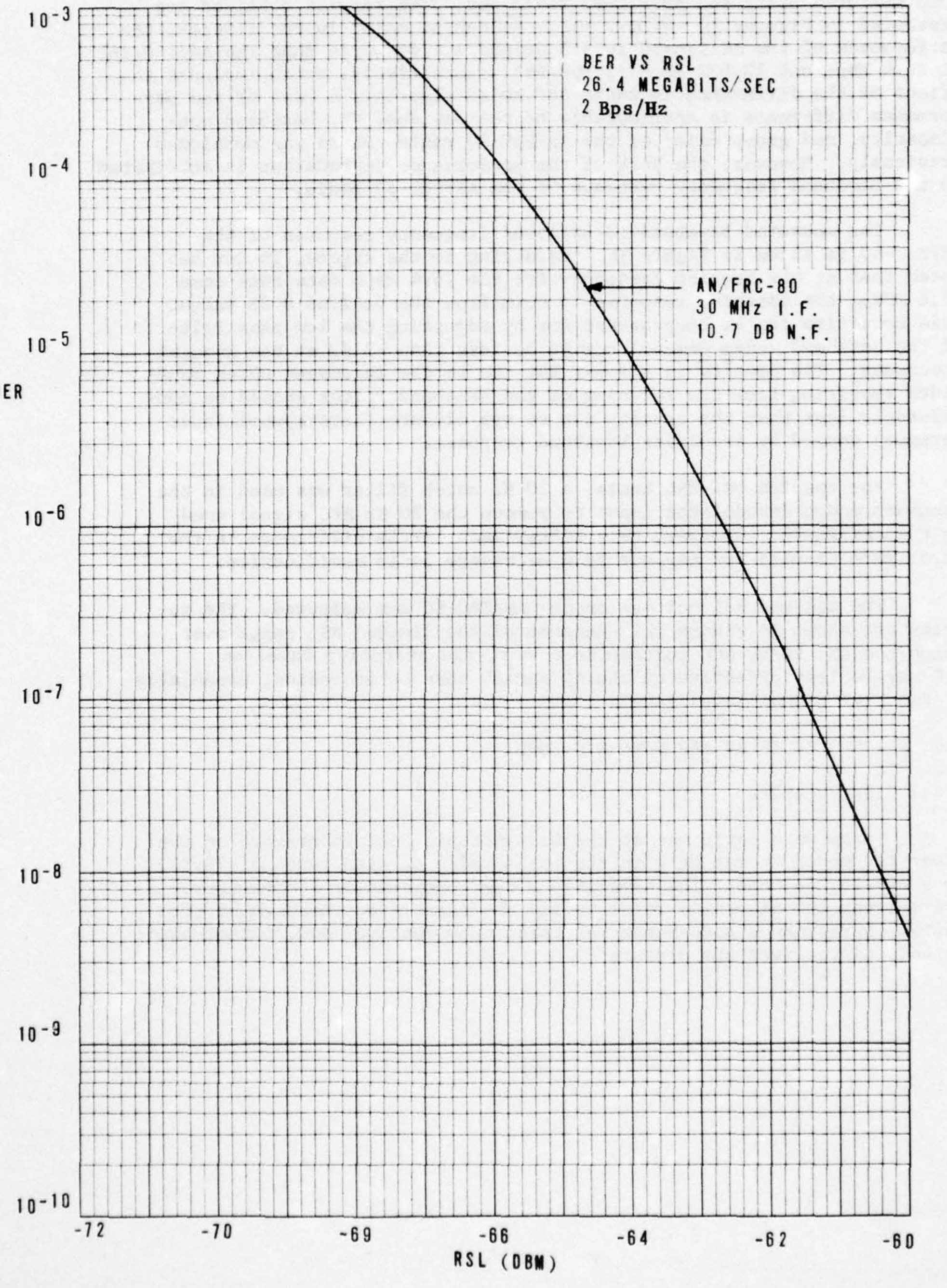


FIGURE 29

BER VS RSL FOR DAU MODEM WITH MOTOROLA AN/FRC 80 MICROWAVE RADIO

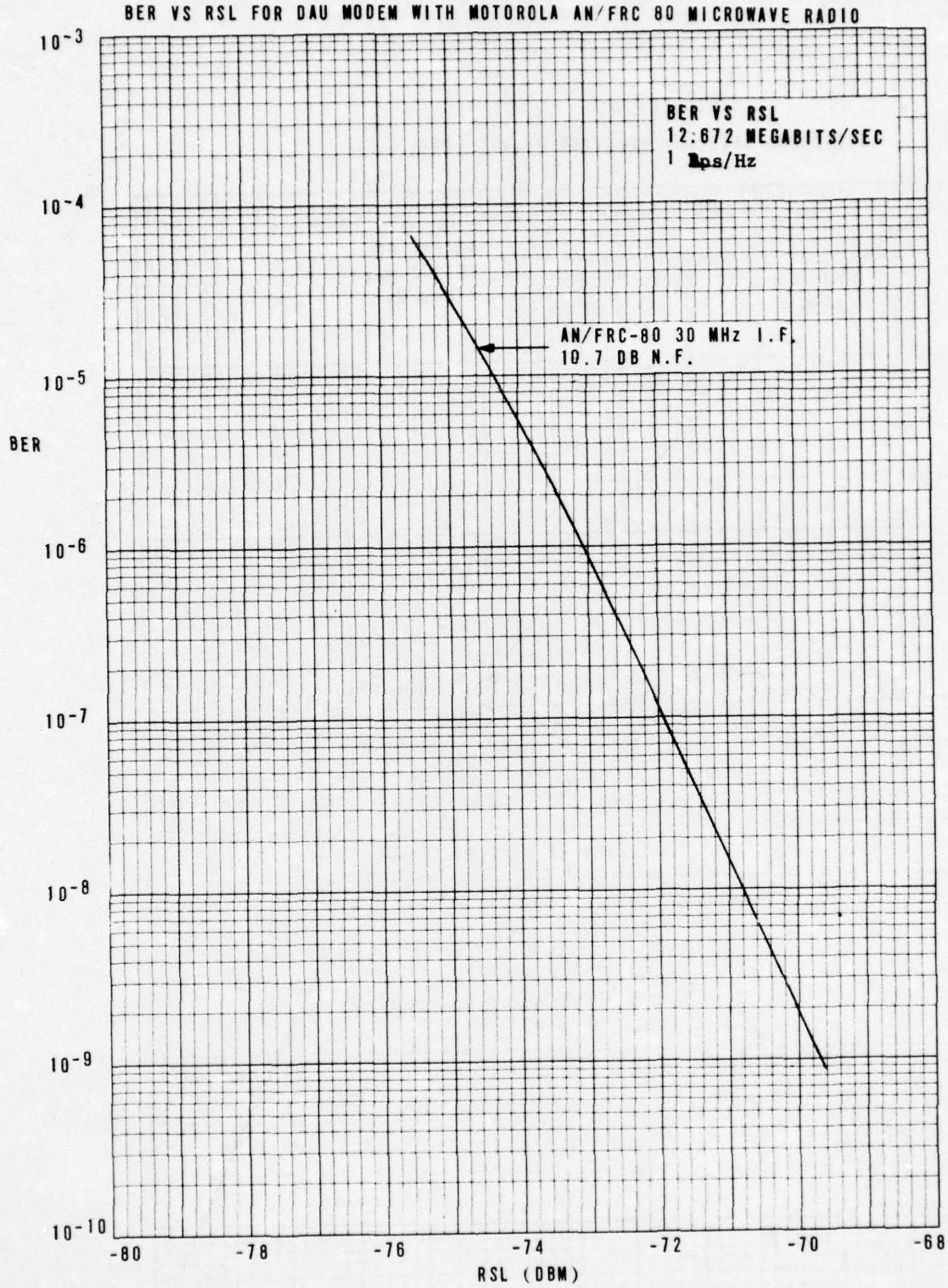
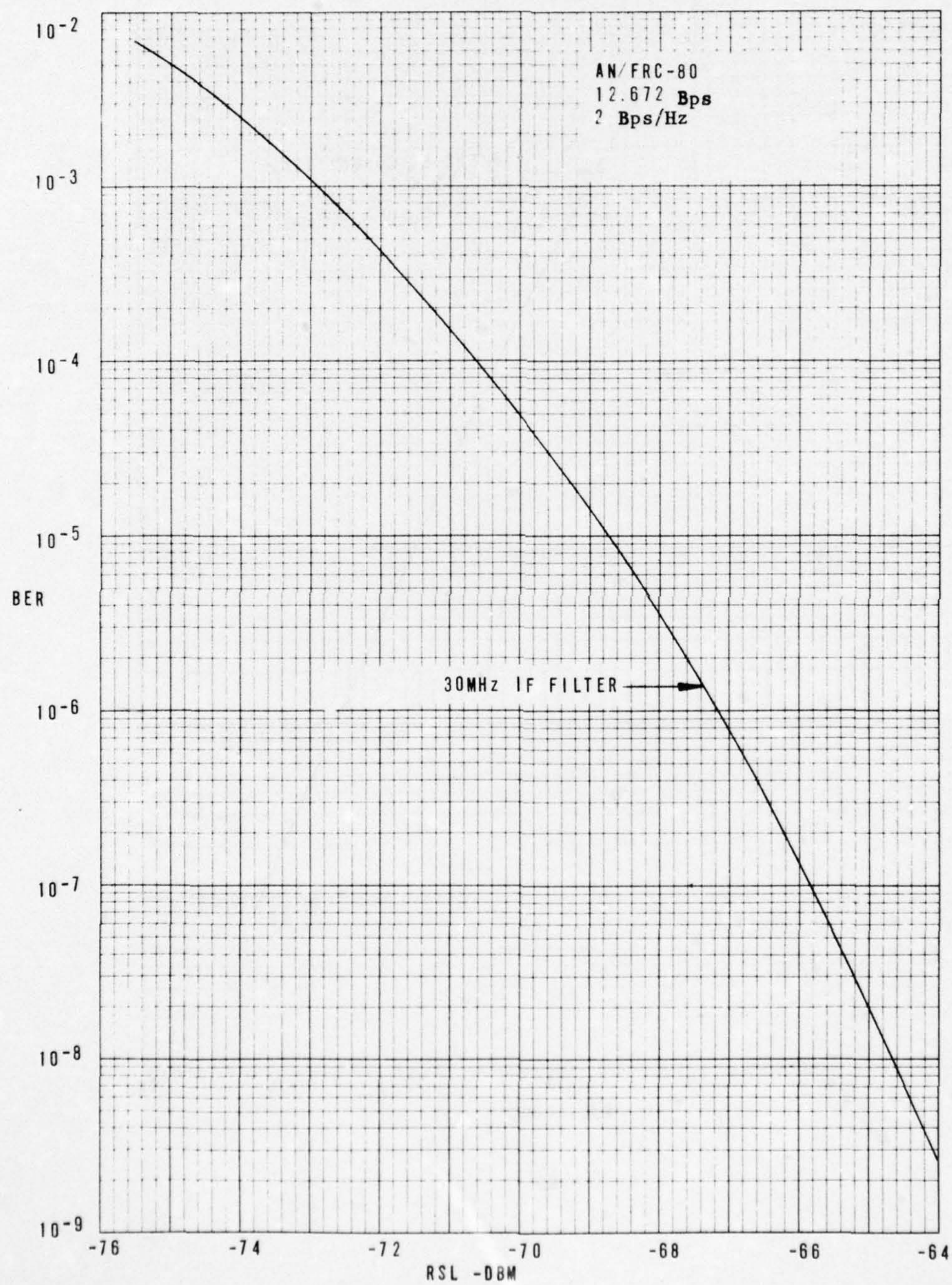


FIGURE 30

BIT ERROR RATE VS. RECEIVED SIGNAL LEVEL



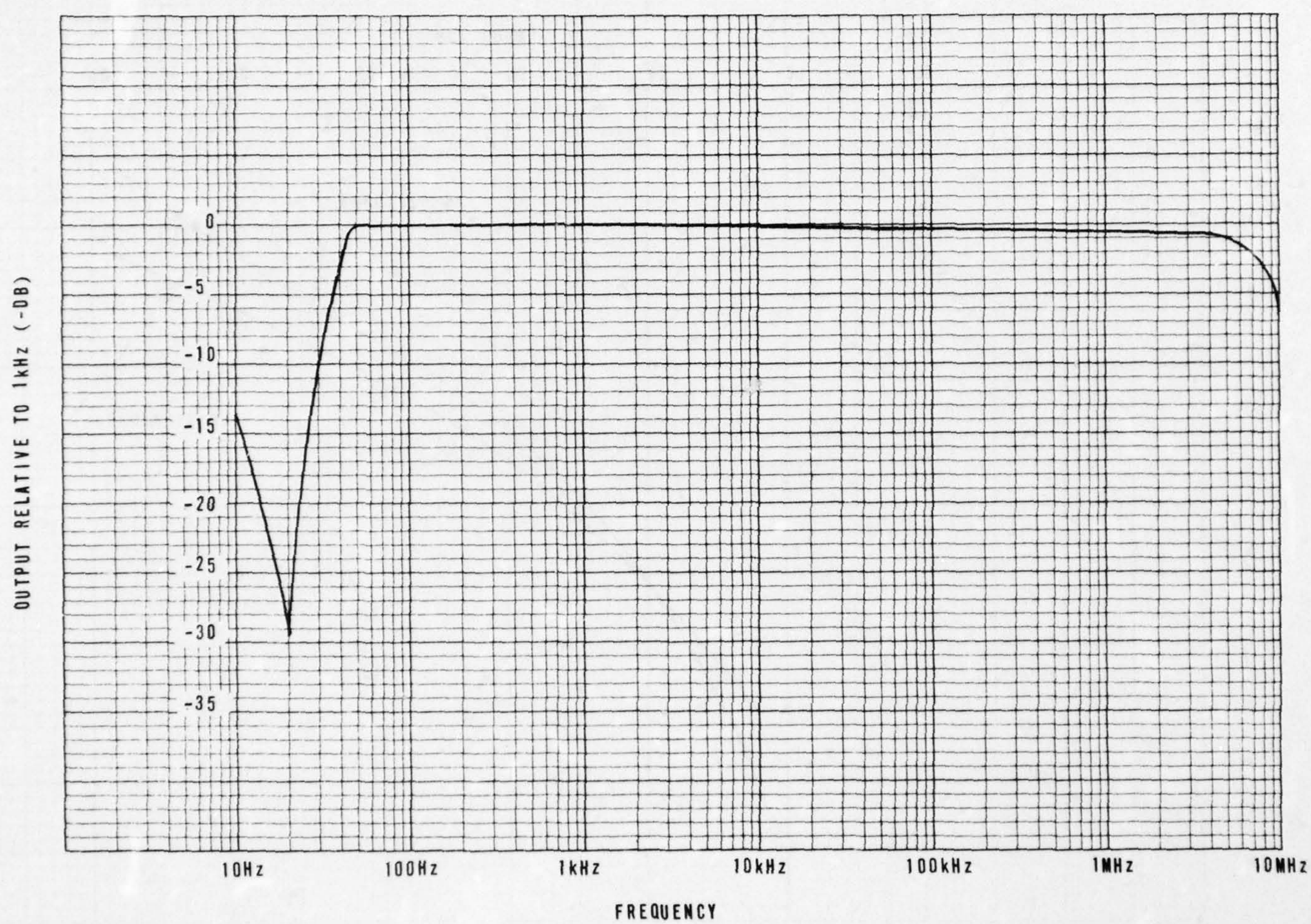
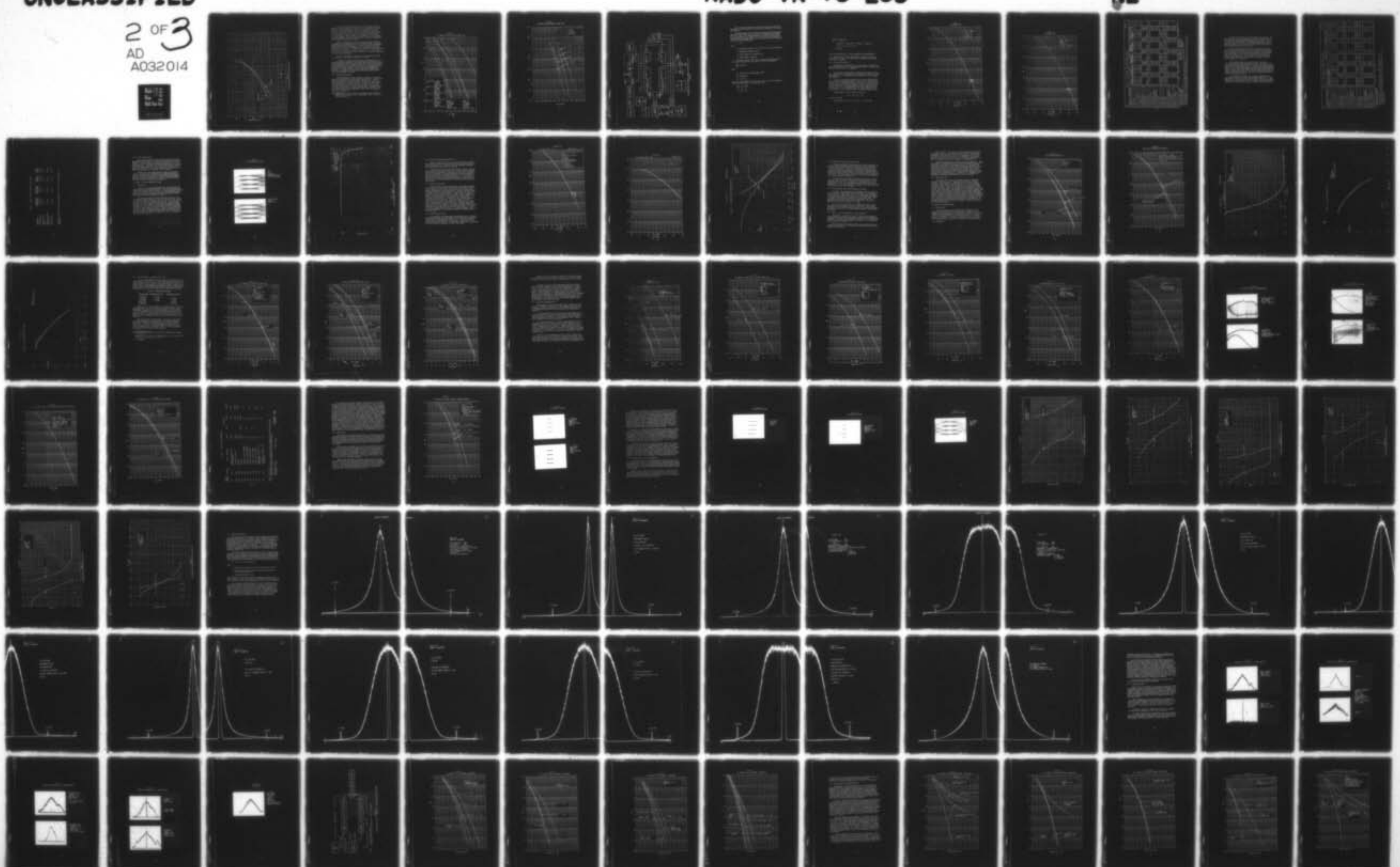


FIGURE 31
BASEBAND FREQUENCY RESPONSE FOR AN/FRC-80 RADIO

AD-A032 014 AERONUTRONIC FORD CORP WILLOW GROVE PA RADIO TRANSMI--ETC F/G 17/2
MICROWAVE DATA TRANSMISSION TEST PROGRAM DIGITAL APPLIQUE UNIT.(U)
AUG 76 F A JESSEN, N G JONES, J W LAYER F30602-73-C-0203
UNCLASSIFIED RADC-TR-76-268 NL

2 OF 3
AD
A032014



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2 OF 3

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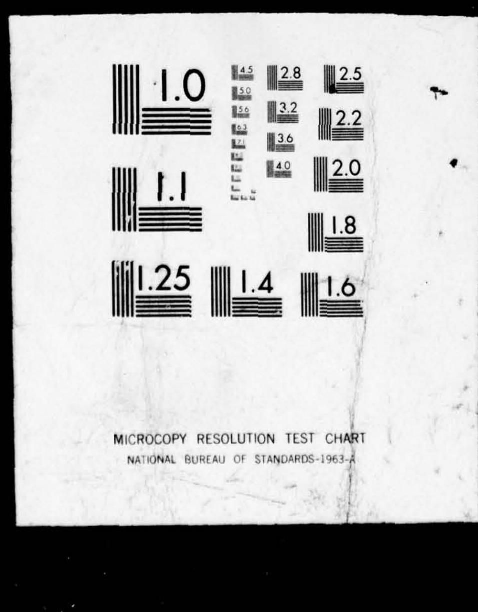
A032014



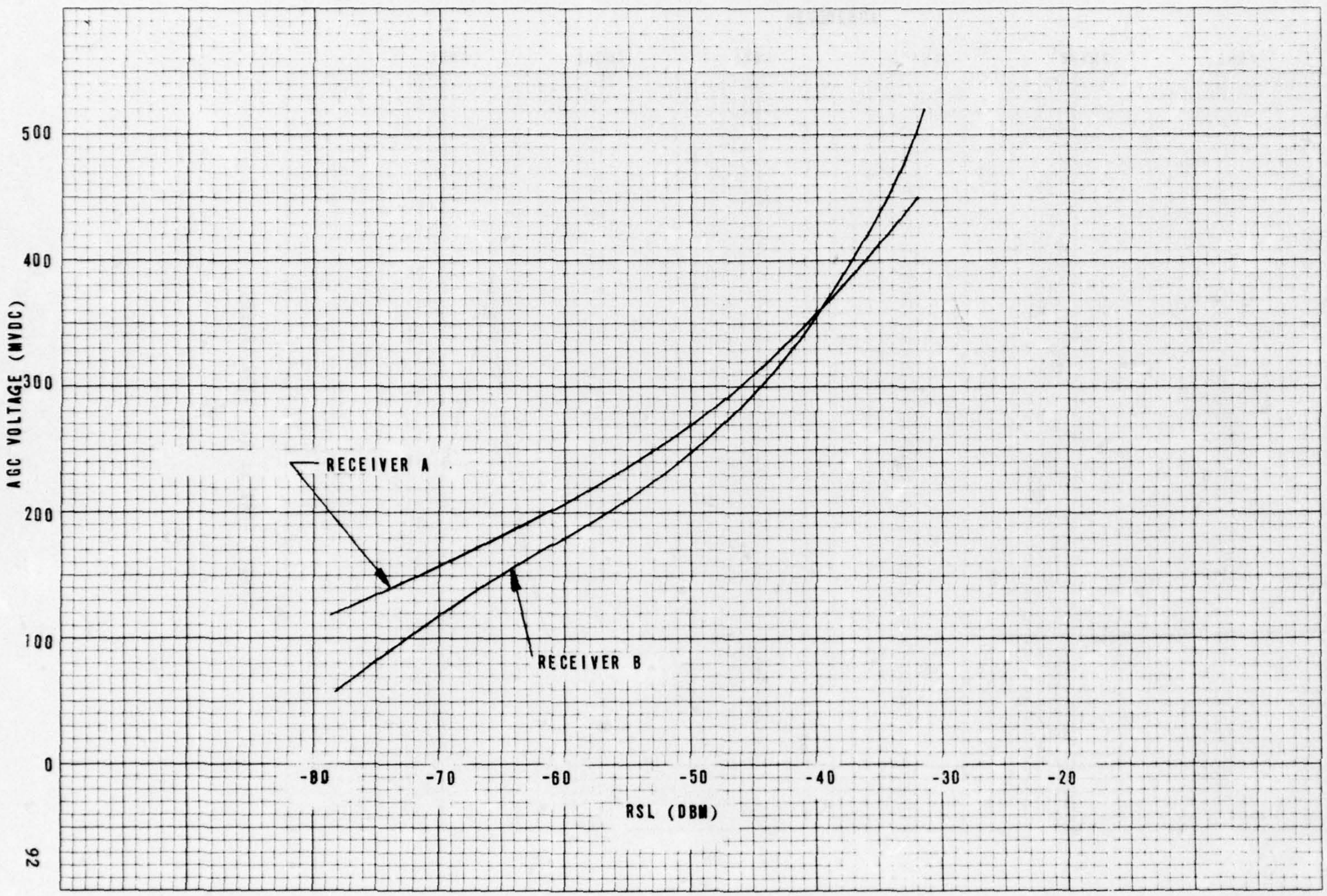


FIGURE 32
AGC CHARACTERISTIC OF THE AN/FRC-80 RADIO

The first part of the testing activity was devoted to the measurement of BER vs. RSL at 26.4 Mbps (2 Bps/Hz), 12.672 Mbps (1 Bps/Hz and 2 Bps/Hz), and 3.168 Mbps (1 Bps/Hz) as a function of IF filter bandwidth. The results indicate that for a data rate of 26.4 Mbps (2 Bps/Hz) the 15 MHz IF filter provides results 0.6 dB better than the 25 MHz IF filter. Comparing 12.672 Mbps (1 Bps/Hz) and 12.672 Mbps (2 Bps/Hz) results using the same IF filter bandwidth of 15 MHz shows a 1.8 dB difference. At a data rate of 3.168 Mbps (1 Bps/Hz), the BER vs. RSL performance using the 15 MHz IF filter is about 3 dB superior to that obtained with the 25 MHz IF filter.

Figure 33 illustrates the BER vs. RSL data taken at 26.4 Mbps (2 Bps/Hz) and 12.672 Mbps (2 Bps/Hz) for the three radios investigated, LC-4A, AN/FRC-162, and AN/FRC-80, all with 25 MHz IF filter bandwidths (except 30 MHz for AN/FRC-80 radio). The LC-4A and AN/FRC-162 radios were essentially equal in performance, while the AN/FRC-80 radio was judged to be 4 dB inferior. The degradation encountered with the AN/FRC-80 is due to the factors discussed in the Phase 2 tests; especially the relatively poor baseband frequency response, which was not compensated for, due to time limitations.

Figure 34 illustrates the effect of IF filter bandwidth on BER vs. RSL for the LC-4A radio at 12.672 Mbps (1 Bps/Hz).

In addition to the above described tests, acceptance test on the diversity modem was performed at the Aeronutronic Ford laboratory as part of the Phase 3 effort. The test set-up employed for the conducting of the acceptance test is depicted in Figure 35. A complete discussion of this phase of the testing effort may be found in the acceptance test report[5]. It should, however, be noted that the performance level achieved with the DAU satisfied all of the applicable program specifications. In essence, it can be stated that the acceptance test effort was unequivocally successful.

4.4.2 BER Data Presentation

The BER performance can be specified in terms of RSL directly which is very useful from a system engineering viewpoint. However, BER performance specified in terms of RSL is a function of a number of implicit variables including noise figure and data rates which makes rapid comparison of performance difficult. A preferred way of expressing BER performance is as a function of E_b/N_o (Energy per bit in a one Hertz noise bandwidth). E_b/N_o permits comparison of performance of a digital system without direct reference to such variables as radio receiver noise figure and IF bandwidth. A BER of 10^{-7} at an E_b/N_o of 24 dB was a design goal.

(5) Acceptance Test Report of the DAU Development Program, Contract Number F30602-73-C-0203, Rome Air Development Center, Griffiss Air Force Base, New York.

FIGURE 33
BIT ERROR RATE VS. RECEIVED SIGNAL LEVEL

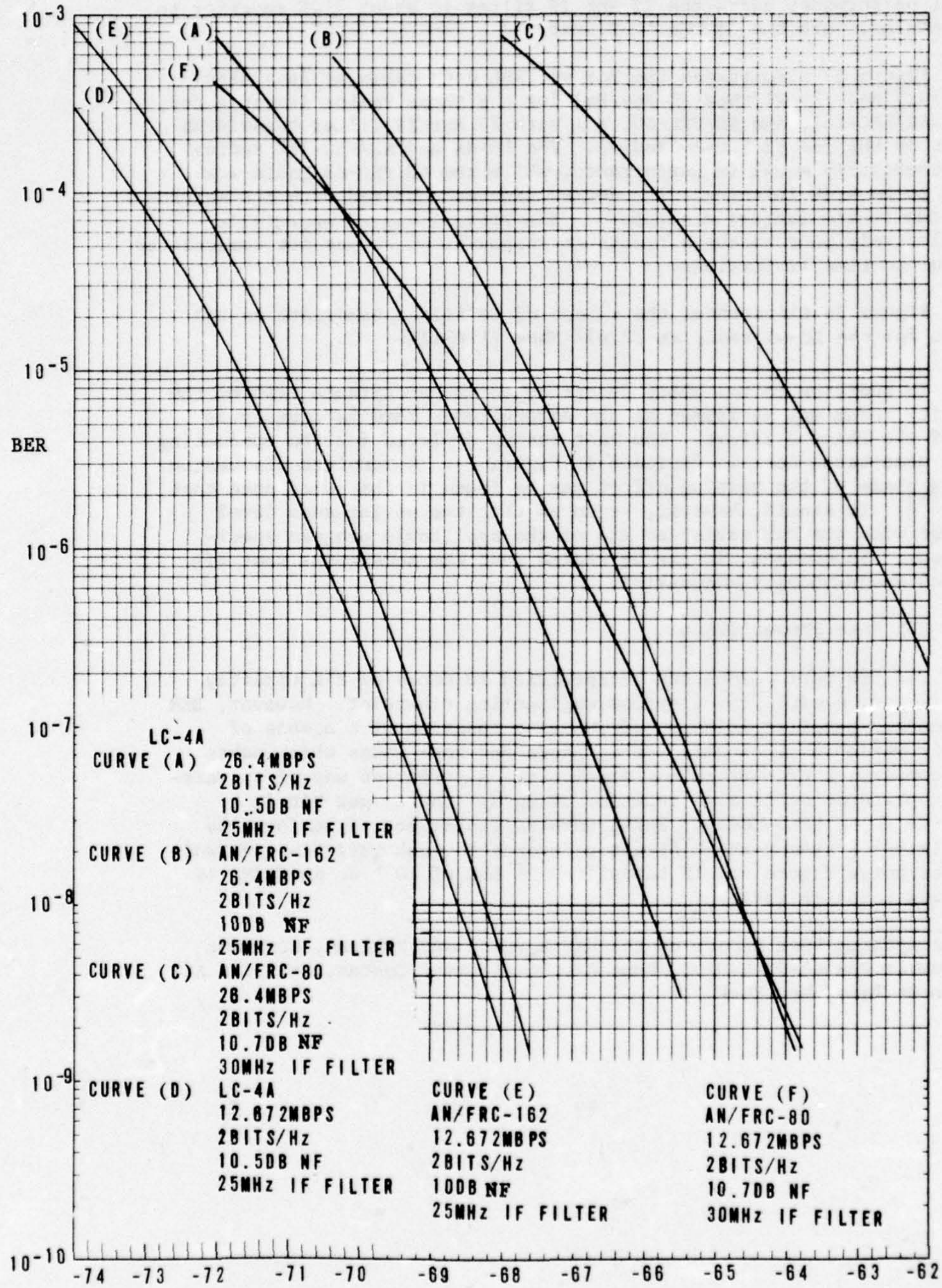
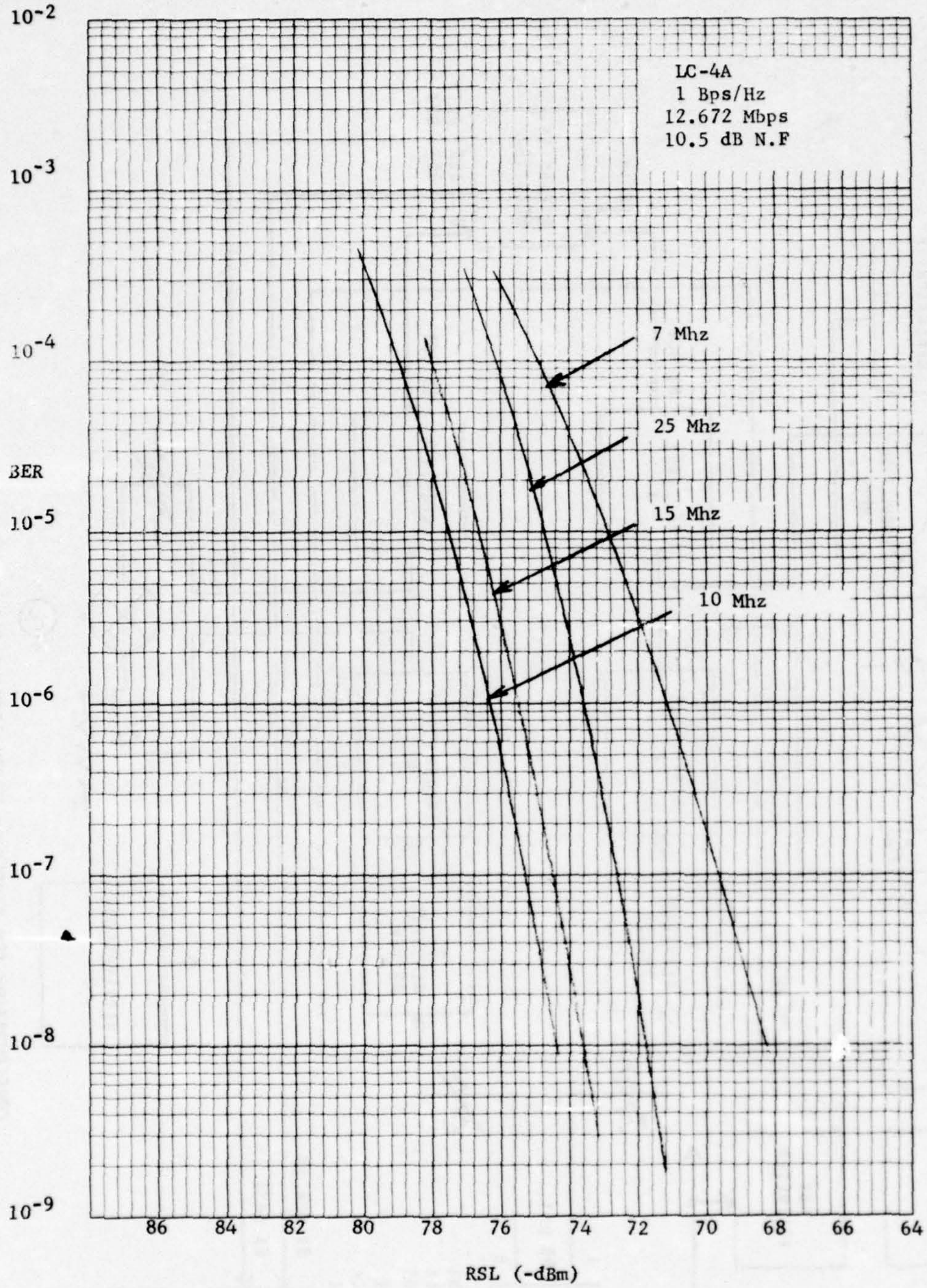
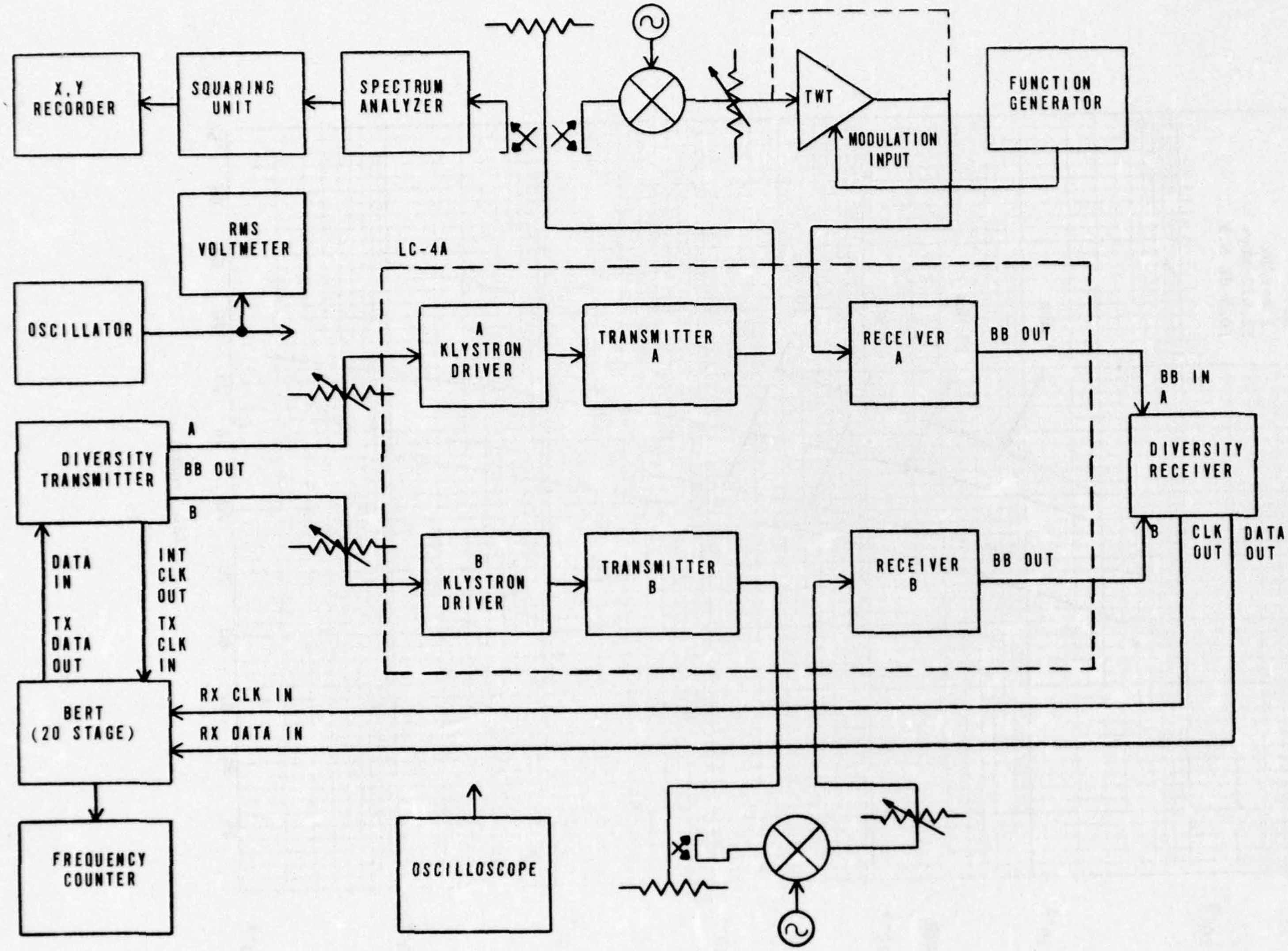


FIGURE 34
BIT ERROR RATE VS. RECEIVED SIGNAL LEVEL





CONFIGURATION FOR DIVERSITY MODEM TESTING WITH LC-4A
FIGURE 35

E_b/N_o can be calculated using the RSL, receiver noise figure and data rate. A brief description of the method is presented in the following paragraph.

The calculations will be described using an *illustrative example*. Assume for this example that a BER of 10^{-7} was obtained for a measured RSL of -65.9 dBm. It is further assumed that the noise figure and the IF noise bandwidth of the receiver is 10.2 dB and 25 MHz, respectively. The noise power referenced to the input of the receiver can be determined using the following relationship:

$$N = KBTF$$

where:

K = Boltzmann's constant (1.38×10^{-23} Joules per degree Kelvin)

T = Temperature (degrees Kelvin)

B = Noise bandwidth of receiver in Hz

F = Noise figure of receiver

The carrier-to-noise ratio C/N is related to the energy per bit to the noise power density ratio, E_b/N_o in the following manner:

$$\frac{E_b}{N_o} = \frac{1}{2} \frac{C}{N} BT_S$$

where:

T_S = Duration of a received data symbol

R_S = Symbol rate

R_B = Bit rate

Based on a noise figure of 10.2 dB, a bit rate, R_B, of 26.112 megabits per second, E_b/N_o takes on the indicated value

$$\frac{E_b}{N_o} = \frac{1}{2} \frac{C}{N} BT_S$$

$$T_S = \frac{1}{R_S} = \frac{2}{R_B}$$

$$\frac{E_b}{N_o} = \frac{1}{2} \quad \frac{C}{KTF} \; \frac{2}{R_B}$$

$$= 10\log_{10} C - 10\log_{10} (KT) - 10\log_{10} F - 10\log_{10} R_B$$

$$= -65.9 + 114 - 10.2 - 14.12$$

$$\approx 23.8 \text{ dB}$$

where the relationship $T_S = 2/R_B$ was employed in the calculations.

Figures 36 and 37 are plots of BER vs. RSL and E_b/N_o for an LC-4A radio. An E_b/N_o of less than 24 dB was required to give a BER of 10^{-7} at 26.112 Mbps.

4.4.3 Radio System Analysis

An analysis of the DAU/radio will be performed to indicate the fade margin attainable over a typical microwave system. Then the system gain of various radios will be computed.

To calculate the fade margin of a DAU/radio, an E_b/N_o of 24 dB for a BER of 10^{-7} at 27.648 Mbps with 2 Bps/Hz will be used. This data rate corresponds to a transmission rate obtained with two 12.672 Mbps data sources.

Table 10 shows typical calculations for three different radios on a link with the parameters shown in lines 2 and 5. Line 6 and the noise figure are specification values. Line 10 is line 6 minus lines 7 and 8. Line 17 is the DAU-radio input threshold for a BER of 10^{-7}. The input threshold is obtained from E_b/N_o (24 dB), which corresponds to C/N = 23.6 dB in a noise bandwidth of 26.2 MHz (nominal for a 25 MHz IF filter). The transmission rate of 27.648 Mbps (data rate of 2 x 12.672 Mbps) is 14.4 dB over 1 MHz. The input threshold is then

$$\text{Input Threshold} = kT_o + 10 \log BW + C/N + NF$$

$$= -114 + 14.4 + 23.6 + NF$$

and, for the LC-8D

$$\text{Input Threshold} = -114 + 14.4 + 23.6 + 11 = -65.0 \text{ dBm.}$$

FIGURE 36
LC-4A BER VS RSL

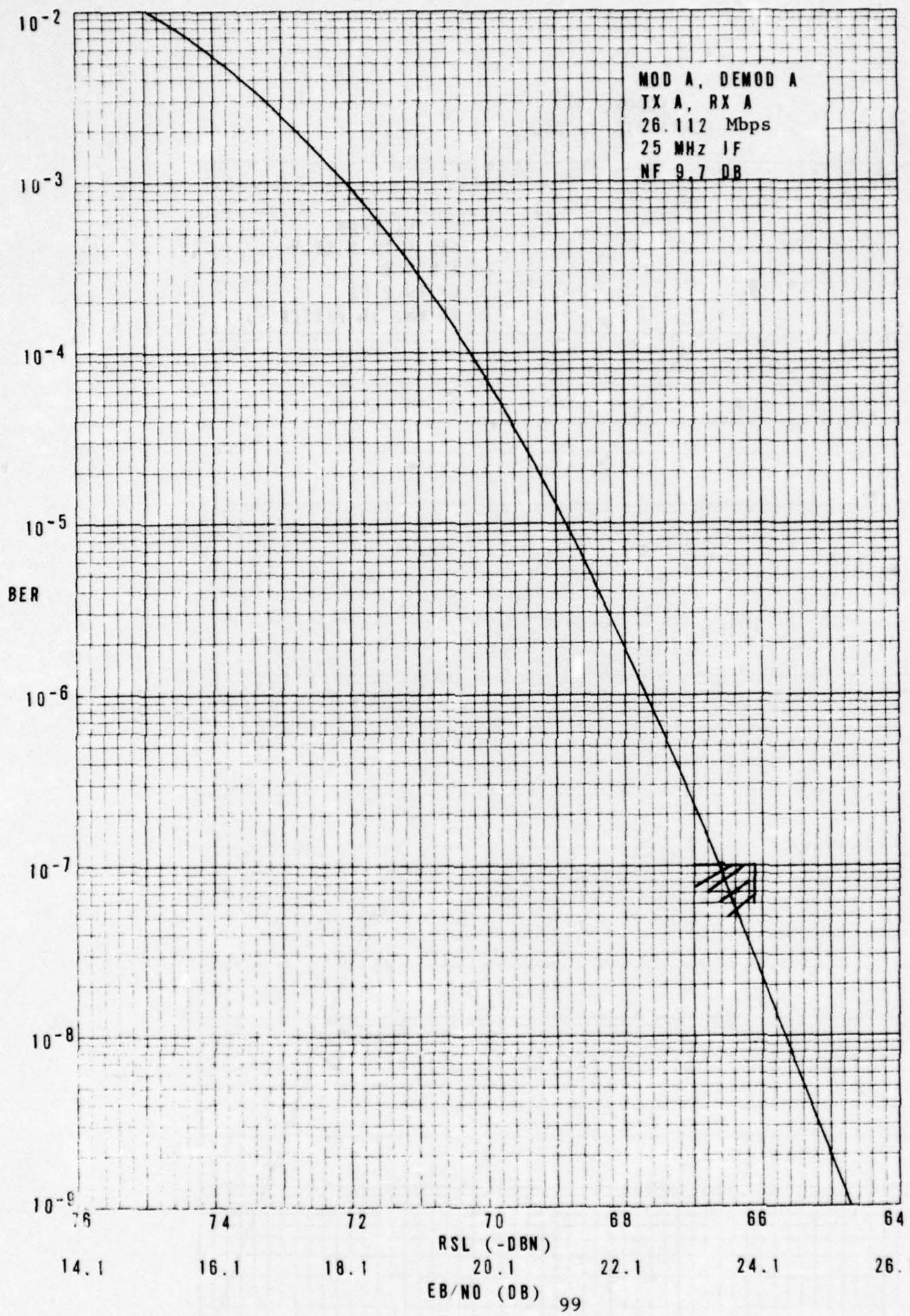
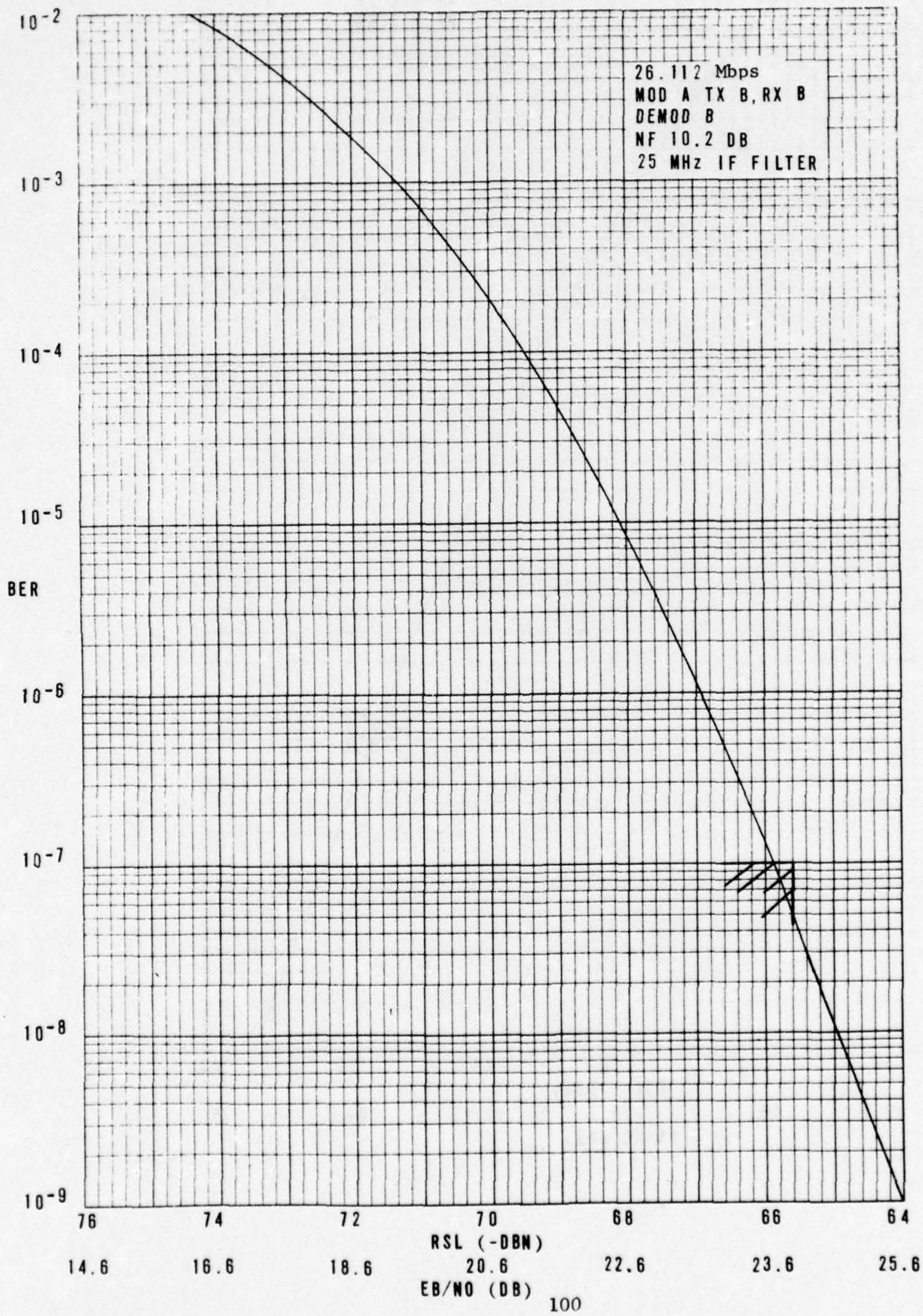


FIGURE 37
LC-4A BER VS RSL



SD-684D

TABLE 10. RF LEVEL CALCULATION SHEET

CUSTOMER: SCOPE COMM NO. FREQ. 8.400 GHz RF. EQUIP. 8 GHz Radio

1	STATION		LC-8D NON-DIVERSITY			LC-8D NON-DIVERSITY			AN/FRC-80 NON-DIVERSITY			AN/FRC-162 NON-DIVERSITY			LC-8D DIVERSITY		
2	PATH LENGTH	mi.	30			30			30			30			30		
3	REQUIRED TOWER HEIGHT	ft.															
4	ANT.-REFL. SPACING	ft.															
5	WAVEGUIDE RUN	ft.	25	25		25	25		25	25		25	25		25	25	
6	TX Power Output [1]	dBm			+38			+38			+28.5			+27			+38
7	FREE SPACE LOSS	db			145			145			145			145			145
8	WAVEGUIDE LOSS	db	EW-71		3.8	EW-71		3.8	EW-71		3.8	EW-71		3.8	EW-71		3.8
9	ADDITIONAL LOSS [2]	db															
10	RECEIVED SIGNAL LEVEL WITHOUT GAIN	dBm			-110.8			-110.8			120.3			-121.8			-110.8
11	RECEIVED SIGNAL LEVEL FOR SPECIFIED FADE MARGIN [1]	dBm			-25			-25			-24			-26			-40
12	REQUIRED MINIMUM ANTENNA GAIN	db			85.8			85.8			96.3			95.8			70.8
13	ANTENNA SIZE	ft.	8	10		8	8		10	10		10	10		4	4	
14	REFLECTOR SIZE	ft.															
15	ACTUAL ANTENNA SYSTEM GAIN	db	42.6	45.4	88.0	42.6	42.6	85.2	45.4	45.4	90.8	45.4	45.4	90.8	36.5	36.5	73.0
16	CORRECTION TO FADE MARGIN	db			+2.2			-.6			-5.5			-5.0			+2.2
17	MIN. USABLE RECEIVED SIGNAL LEVEL [1]	dBm			-65			-65			-64			-66			-65
18	ACTUAL FADE MARGIN	db			42.2			39.4			34.5			35			27.2
19	ACTUAL NORMAL RECEIVED SIGNAL LEVEL	dBm			-22.8			-25.6			-29.5			-31.0			-37.8
			NF = 11 dB			NF = 11 dB			NF = 12 dB (.5dB worse with Freq.Diversity)			NF = 10 dB Higher Power Transmitter is Optional			NF = 11 dB		

1. DEPENDS ON RF EQUIP. SELECTED.
2. ITEMIZE ADDITIONAL LOSSES.

E_b/N_o of 24 dB for BER = 10^{-7}
Receiver Threshold 23.6 dB in 25 MHz (3dB BW) @ BER = 10^{-7} and 2 Bps/Hz @ 27.648.
40 dB Fade Margin for 99.99% Path Reliability with No Diversity.
25 dB Fade Margin for 99.99% Path Reliability with Space or Frequency Diversity and Rayleigh Fading.

For Non-Diversity, line 11 is 40 dB greater than line 17. For Diversity, line 11 is 25 dB greater than line 17. In each case, the path reliability for Rayleigh fading will be 99.99 percent. Line 12 is the required antenna gain, the difference between lines 10 and 11. Line 16 is line 15 minus line 12. The fade margin achieved with the antennas selected (line 13) is shown on line 18, the sum of line 16 and the desired fade margin (40 or 25 dB).

The fifth column of Table 10 shows a Diversity calculation, while the first four columns are for Non-Diversity cases. The results of the computations show that it is easy to achieve the desired BER with a fade margin for 99.99 percent path reliability with available radios and antennas. Dual Diversity computations show that 99.99 percent path reliability is easy to obtain, and that by using only slightly larger antenna gain, an arbitrarily high path reliability can be achieved for a BER of 10^{-7}.

The identical calculations were performed for the DAU and the Aeronutronic Ford LC-4D microwave radio. The results of the calculations are tabulated in Table 11. As can be noted in the table, the actual fade margin calculated for a non-diversity configuration was 40.5 dB. This value of fade margin translates into a path reliability figure of better than 99.999 percent when the modem and radio are configured for diversity operation. The results of these calculations as well as those conducted for the 8 GHz case are summarized in terms of microwave radio gain in Table 12.

Path reliability as used in the preceding paragraphs is the percentage of time that the error rate is better than 1×10^{-7}. The calculations do not include long term variability which would increase the path loss allocations by 2 to 3 dB. However, the path reliability, 99.999, would still be achieved with this factor taken into account.

SD-CS4D

TABLE 11. **RF LEVEL CALCULATION SHEET**

CUSTOMER: SCOPE COMM   NO.   FREQ. 5.000 GHz   RF. EQUIP. 4 GHz

1	STATION		LC-4D NON-DIVERSITY			LC-4D DIVERSITY		
2	PATH LENGTH	mi.	30			30		
3	REQUIRED TOWER HEIGHT	ft.						
4	ANT.-REFL. SPACING	ft.						
5	WAVEGUIDE RUN	ft.	25	25		25	25	
6	TX Power Output [1]	dBm			+ 38			+ 38
7	FREE SPACE LOSS	db			140.4			140.4
8	WAVEGUIDE LOSS	db	EW-37		0.7	EW-37		0.7
9	ADDITIONAL LOSS [2]	db						
10	RECEIVED SIGNAL LEVEL WITHOUT GAIN	dBm			-103.1			-103.1
11	RECEIVED SIGNAL LEVEL FOR SPECIFIED FADE MARGIN [1]	dBm			-26.0			-41
12	REQUIRED MINIMUM ANTENNA GAIN	db			79.1			62.1
13	ANTENNA SIZE	ft.	8	8		4	4	
14	REFLECTOR SIZE	ft.						
15	ACTUAL ANTENNA SYSTEM GAIN	db	38.8	38.8	77.6	32.3	32.3	64.6
16	CORRECTION TO FADE MARGIN	db			+0.5			+2.5
17	MIN. USABLE RECEIVED SIGNAL LEVEL [1]	dBm			-66.0			-66
18	ACTUAL FADE MARGIN	db			40.5			27.5
19	ACTUAL NORMAL RECEIVED SIGNAL LEVEL	dBm			-25.5			-38.5
			NF = 10 dB			NF = 10 dB		

1. DEPENDS ON RF EQUIP. SELECTED.
2. ITEMIZE ADDITIONAL LOSSES.

Receiver Threshold 25.2 dB in 25 MHz @ BER = 10^{-7} and 2 Bps/Hz @ 26.4 Mbps.
40 dB Fade Margin for 99.99% Path Reliability with No Diversity.
25 dB Fade Margin for 99.99% Path Reliability with Space or Frequency Diversity and Rayleigh Fading.

TABLE 12. GAIN OF VARIOUS MICROWAVE RADIO TYPES

RADIO TYPE	AERONUTRONIC FORD LC-4D	AERONUTRONIC FORD LC-8D	MOTOROLA MR-300	COLLINS 97E1
Transmit Power	+38 dBm	+38 dBm	+28.5 dBm	+27 dBm
Receiver Noise Figure	10 dB	11 dB	12 dB	10 dB
Receiver Threshold @ BER = 10^{-7}	-66 dBm	-65 dBm	-64 dBm	-66 dBm
Net Radio Gain	104 dB	103 dB	92.5 dB	103 dB

Receiver threshold for quaternary baseband FM is 23.6 dB C/N @ 27.648 Mbps and 2 Bps/Hz.

4.4.4 Filter Considerations

The baseband transmit and receive filters used for the LC-4A measurements are designed to produce a received baseband raised cosine spectrum. Since the LC-4A has an amplitude adjustment in the transmitter, the overall baseband to baseband response was set to 0 dB at the Nyquist rate. The transmit and receiver baseband filter responses were each down approximately -3 dB at the Nyquist frequency (6.528 MHz) of the symbol rate. The Nyquist frequency of the symbol rate is equal to one quarter of the total MBS rate in frequency.

Baseband group delay equalization was used in the receiver filter to compensate for the effects of the transmit and receive filters. The preliminary filter values were computer optimized for amplitude and group delay response. A Wandel and Goltmann baseband amplitude and group delay test set was used to align the filters to verify that the design parameters were achieved.

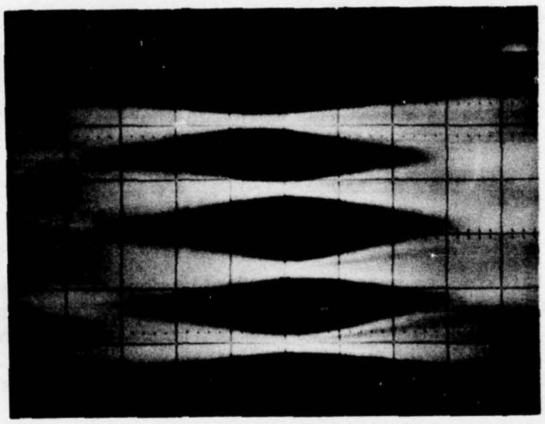
4.5 PHASE 4 DIVERSITY MODEM TEST AT RADC

4.5.1 Introduction

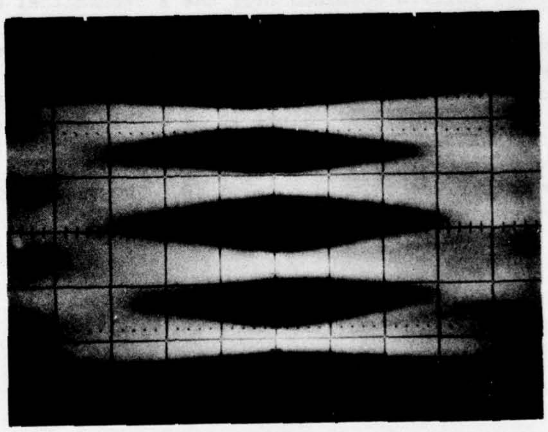
Tests on a diversity modem operating at 26.112 Mbps were conducted at RADC on an LC-8D TWT type radio. The diversity modem tests at RADC were conducted for two reasons: to provide performance information for those systems which do not require a digital MBS-SCBS multiplexer, and secondly, to provide test results which could be used as a base before the MBS-SCBS multiplex was added.

The primary interfacing problem encountered using the LC-8D was baseband frequency response at the 26.112 Mbps data rate. Figure 38 shows the received eye pattern obtained over the B transmitter and receiver of the radio at Griffiss Air Force Base. The eye closure was due to the radio frequency response which was measured and shown in Figure 39. The response is 1.1 dB down at the Nyquist frequency. The bulk of this is due to a roll-off capacitor at the discriminator output of a Scopecomm type LC-8D radio. Since it is highly desirable to avoid any radio modifications, the response was compensated for in the modem. Rather than make the modem receiver filter -3 dB at the Nyquist frequency, the filter was changed to -1.9 dB. The resulting eye is shown in Figure 38.

Figure 38
LC-8D Received Eye Pattern



TX A
RX A
Translator
Modified RX Filter
(1.9 dB @ Nyquist)



Same as above
except
BER of 10^{-7}

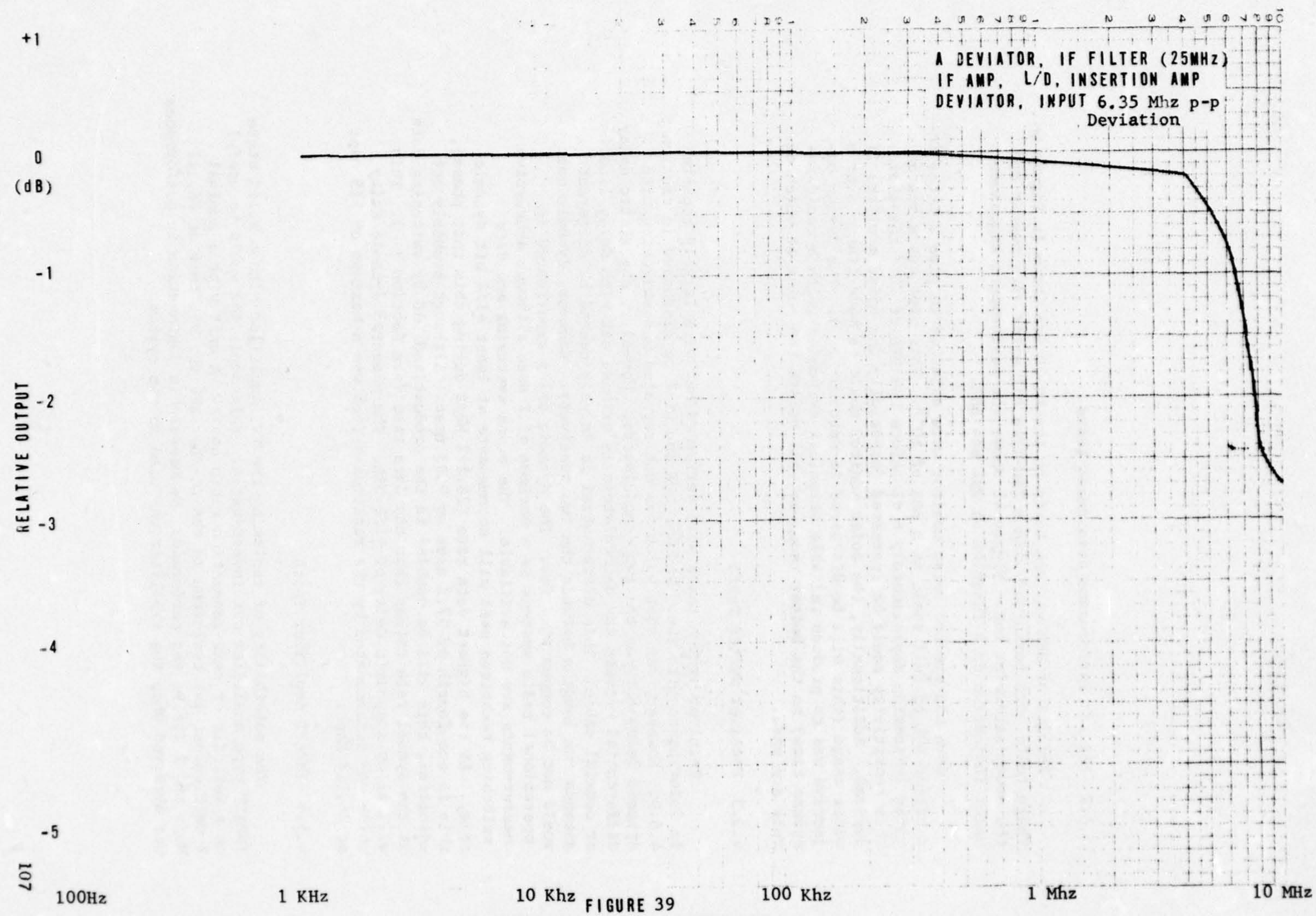


FIGURE 39
LC-8D BASEBAND FREQUENCY RESPONSE

4.5.2 BER and Performance Assessment Tests

Results of BER vs. RSL tests on the LC-8D are shown in Figure 40. These tests were performed with a Tau-Tron bit error rate tester and the modem scrambler out. Figure 41 shows the performance assessment meter indication as a function of RSL and BER.

Both the eye and noise monitor were adjusted to give a meter indication 60% of full scale at a BER of 10^{-7}. This produces a readable meter indication approximately 6 dB before the BER of 10^{-7} threshold. This sensitivity could be increased (especially the noise monitor) if desired. Additionally, the noise monitor could be made linear over a wider range (this will be discussed in Section 7). The design objective was to produce reliable errorless switching (with a rapid response time) to the better receiver well before the point at which errors are made.

4.5.3 Receiver Switch Tests

Receiver switch tests were performed but were largely repeated in later tests with the MBS-SCBS MUX and will be discussed in section 4.6.9. However, one test which was not repeated was switching with dynamic delay between the two demodulators. Normally, any static delay differential between the demodulators is trimmed out with delay lines or coaxial cable. This differential is largely caused by different antenna run lengths between the two receivers. However, dynamic delay would not be compensated for. The dynamic delay experienced in operational radio systems is a maximum of 2 nsec although exhaustive measurements are not available. The clock averaging and data switching technique used will accommodate at least $\pm 1/4$ bit dynamic delay. At the highest data rate (26.112 Mbps during this test phase), this is one-fourth of 37.3 nsec or 9.33 nsec. Although probably not essential, this will be doubled in the productized DAU by switching data at the symbol rate rather than the data rate (see Section 7). This will allow a dynamic delay of $\pm 1/2$ bit. The measured dynamic delay which was accommodated by the receiver switch was a maximum of ± 15 nsec at 26.112 Mbps.

4.5.4 IMPATT Amplifier Tests

The possibility of replacing the TWT amplifier with a solid state IMPATT type amplifier was investigated. This amplifier would be useful on a retrofit or next-generation radio basis. A unit with a nominal 2 watt output was evaluated in the LC-8D. BER vs. RSL test at 26.112 Mbps and 2 Bps/Hz was performed. No measurable degradation in performance was observed when the amplifier was used in the system.

Figure 40-A

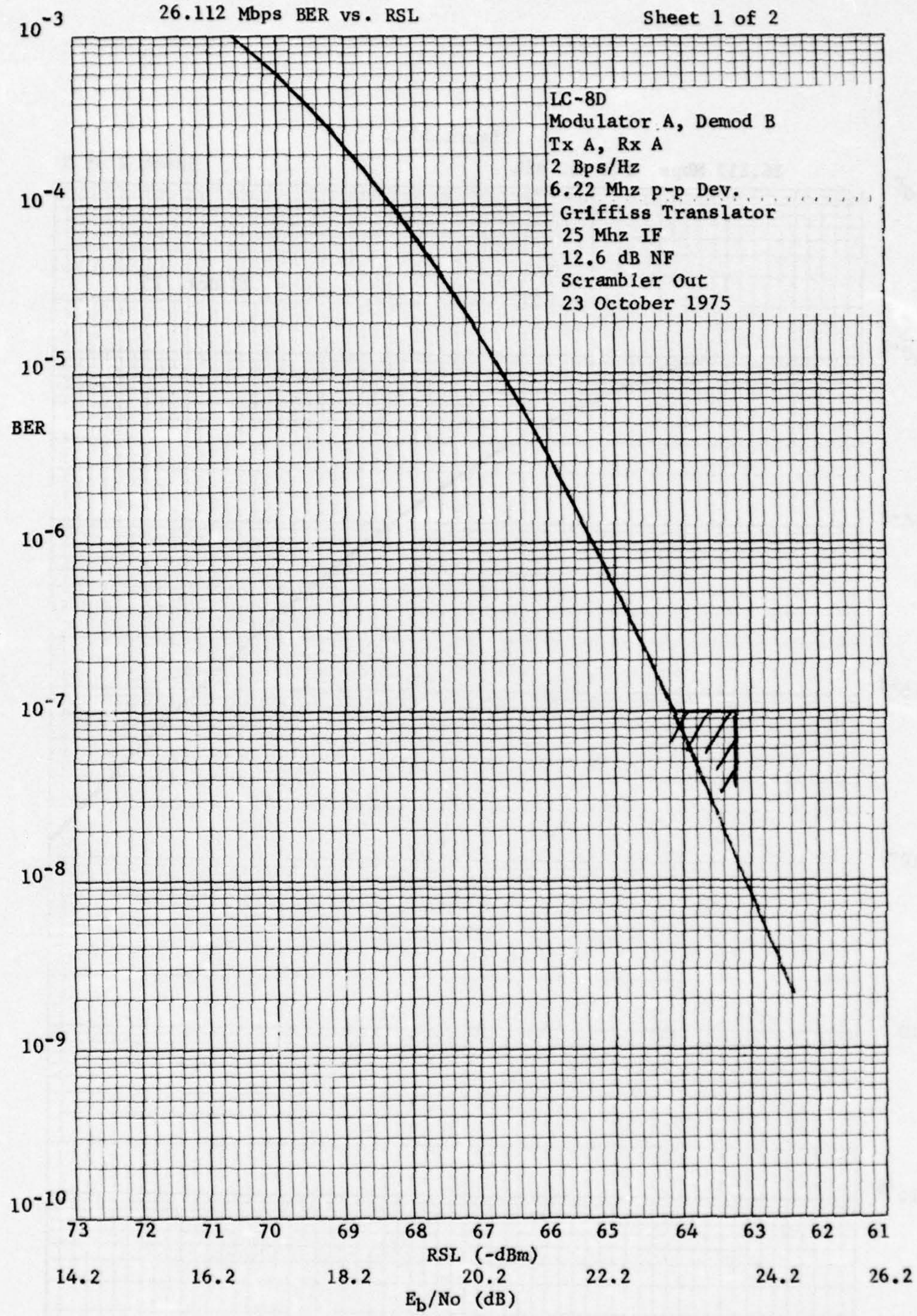

26.112 Mbps BER vs. RSL
Sheet 1 of 2
10^{-3}
10^{-4}
10^{-5}
BER
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
LC-8D
Modulator A, Demod B
Tx A, Rx A
2 Bps/Hz
6.22 Mhz p-p Dev.
Griffiss Translator
25 Mhz IF
12.6 dB NF
Scrambler Out
23 October 1975
73 72 71 70 69 68 67 66 65 64 63 62 61
RSL (-dBm)
14.2 16.2 18.2 20.2 22.2 24.2 26.2
E_b/No (dB)

Figure 40-B

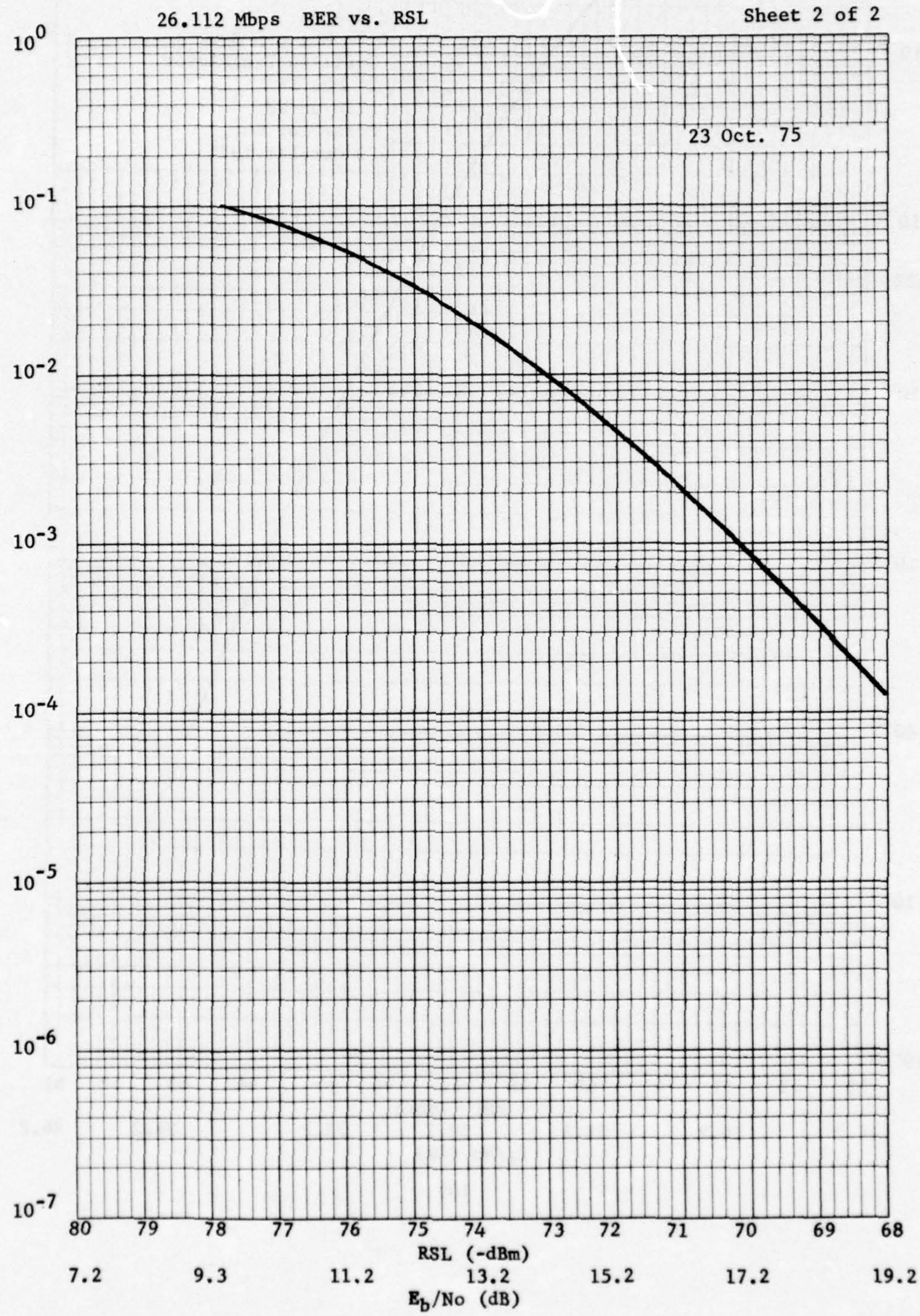
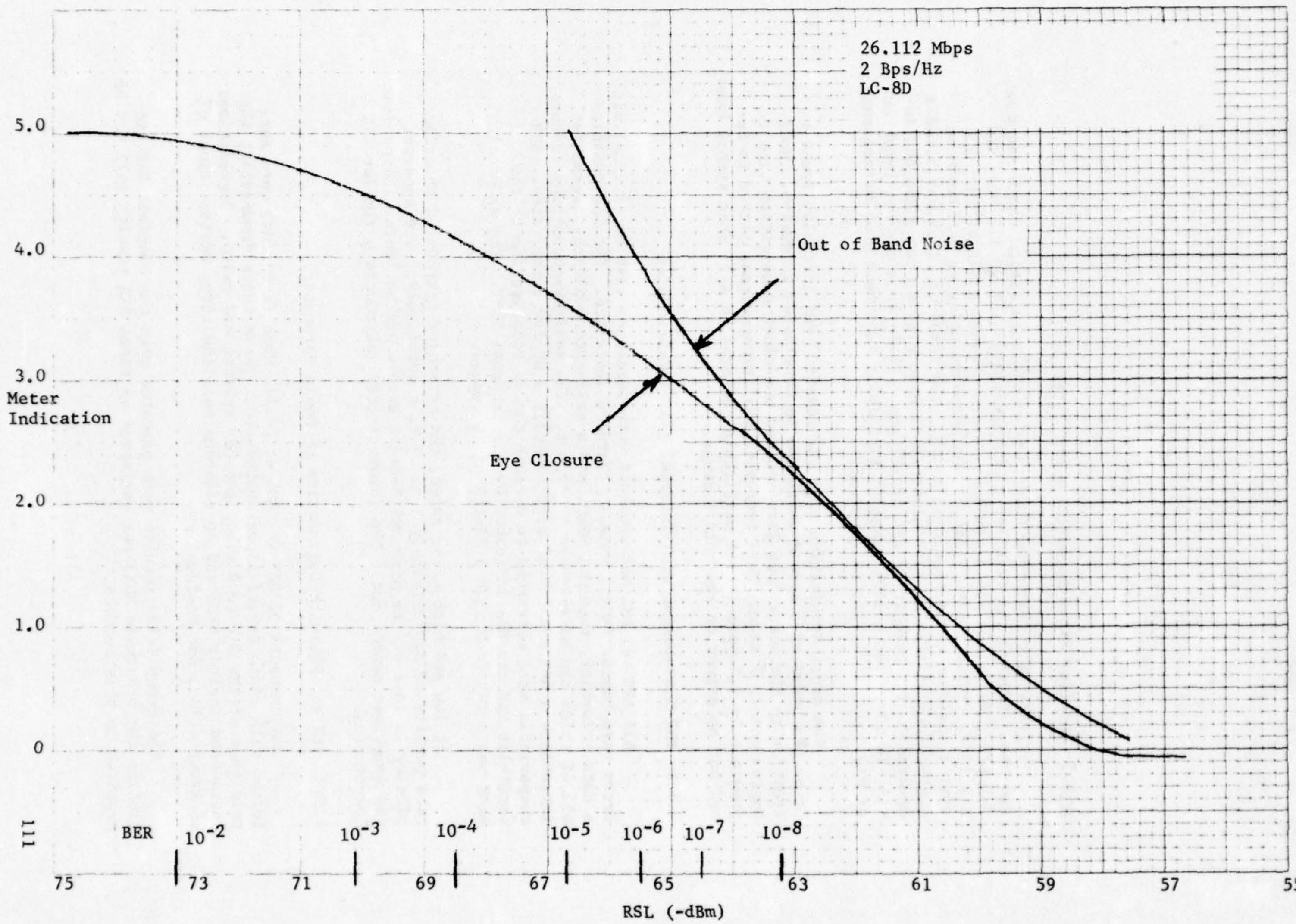

26.112 Mbps BER vs. RSL
Sheet 2 of 2
23 Oct. 75
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
80 79 78 77 76 75 74 73 72 71 70 69 68
RSL (-dBm)
7.2 9.3 11.2 13.2 15.2 17.2 19.2
E_b/No (dB)

Figure 41. PERFORMANCE MONITOR INDICATION vs RSL



4.5.5 Receiver Clock Acquisition and Jitter

Tests were performed to determine the acquisition range and time and the jitter of the receiver clock circuitry. At 26.112 Mbps and 2 Bps/Hz, an RSL of -64.5 dBm and -74 dBm produce a BER of 10^{-7} and 2×10^{-2}, respectively. Jitter was measured using an oscilloscope synchronized on the transmitter clock. The receiver clock exhibited a peak-to-peak jitter of approximately .3 nsec with a strong RSL and increased to 1.5 nsec at an RSL of -82 dBm. Phase lock did not break until -84 dBm. The holdin range is especially important when maintenance of bit count integrity is required.

The clock acquisition time was measured and initially found to be on the order of 1 second which can be considered excessive. Modification to the phase lock loop reduced the clock acquisition time to approximately 7 msec. This increased the strong signal jitter to approximately 1.1 nsec (still negligible compared to a 77 nsec symbol baud) and had no effect on the holdin range.

4.5.6 BER Measurement with Internal BERT and Scrambler

All BER vs. RSL measurements were performed with an external bit error rate tester (BERT) unless otherwise indicated. The DAU contains a data scrambler, internal BERT, and a self-synchronizing descrambler, all of which can be switched in or out. The self-synchronizing feature introduces a BER penalty of approximately 3 at low error rates. BER comparisons were performed to measure the degradation due to the scrambler and the BER indicated by the internal BERT. The external BERT was a Tau-Tron with a length of 20 stages.

At low and high error rates, the scrambler introduced an error rate penalty of approximately 3 and 2.8, respectively. The apparent penalty is less at the high BER because errors are no longer independent and sometimes cancel out. The internal BERT introduces a similar BER degradation.

4.5.7 BER vs. RSL with Degradation of Radio Parameters

Measurements of BER vs. RSL at 26.112 Mbps (2 Bps/Hz) were performed with radio degradations introduced. These tests demonstrate the tolerance of the DAU to a misaligned or substandard radio. Degradations introduced include baseband to baseband non-linearity, various types of IF group delay, and residual FM.

The group delay results were repeated when the complete DAU (including the orderwire MUX) was delivered so those BER results will not be repeated in this section.

Results of BER vs. RSL with low frequency residual FM introduced are given in Figure 42. The modulation was 20 Hz and introduced into a modulatable local oscillator used in the transmitter. This FM simulates the FM of a MR-300 or a noisy L.O. The MR-300 at Fort Huachuca had about 100 kHz p-p residual FM at 20 Hz. The BER vs. RSL results in Figure 42 indicate that the DAU is tolerant of low frequency FM.

The effect of baseband non-linearity is shown in Figure 43 . Baseband linearity is measured (using an HP 3710 link analyzer) from the deviator input to the limiter-discriminator output. An LC-8D will have a baseband non-linearity of less than 2% over ± 5 MHz, typically on the order of 1% over ± 5 MHz. A BER vs. RSL test was made with a normally aligned radio and then with a degraded radio (6% over ± 5 MHz). This is a relatively large amount of non-linearity, greater than would be expected on even a misaligned LC-8D. Non-linearity was introduced by misaligning the Limiter-Discrimination. The BER vs. RSL degradation was negligible at high BER and approximately .4 dB at BER of 10^{-7}.

4.5.8 OBN Monitor Test

The present out of band noise monitor produces a voltage proportional to the peak of the voltage from the OBN filter. The OBN voltage is shown in Figure 44. The range over which the OBN voltage is linear is rather small, approximately 6 dB. This allows switching well before errors are made, but the operation is not as good at relatively strong RSL's. Figure 45 is a plot of the logarithm of the OBN voltage. The linear range is approximately 16 dB. The weak signal range is prematurely limited by a diode (which could be removed) to protect the meter. The strong RSL range is limited by the data signal feedthrough. Figure 46 shows the logarithm of the OBN voltage vs. RSL with the data removed. The high RSL range is extended several dB. The data feedthrough could be reduced by a notch filter in the Baseband Modulator. The logarithm circuitry for the OBN has been designed but not implemented. If the aforementioned improvements are incorporated into the DAU, the performance assessment RSL range would be extended, probably removing the need for monitoring AGC.

4.6 PHASE 5 DAU ACCEPTANCE TEST

4.6.1 Introduction

The DAU equipment was delivered to RADC on December 1, 1975, interfaced with LC-8D radio sets and subjected to evaluation in accordance with the applicable acceptance testing procedure. The DAU included an MBS-SCBS MUX/DEMUX and variable rate clocks. It is the purpose of this paragraph to present and discuss the results of the acceptance test effort.* For purposes of presentation, the test results have been categorized in terms of the characteristic under evaluation.

* See APPENDIX A

Figure 42
BER vs RSL vs RESIDUAL FM

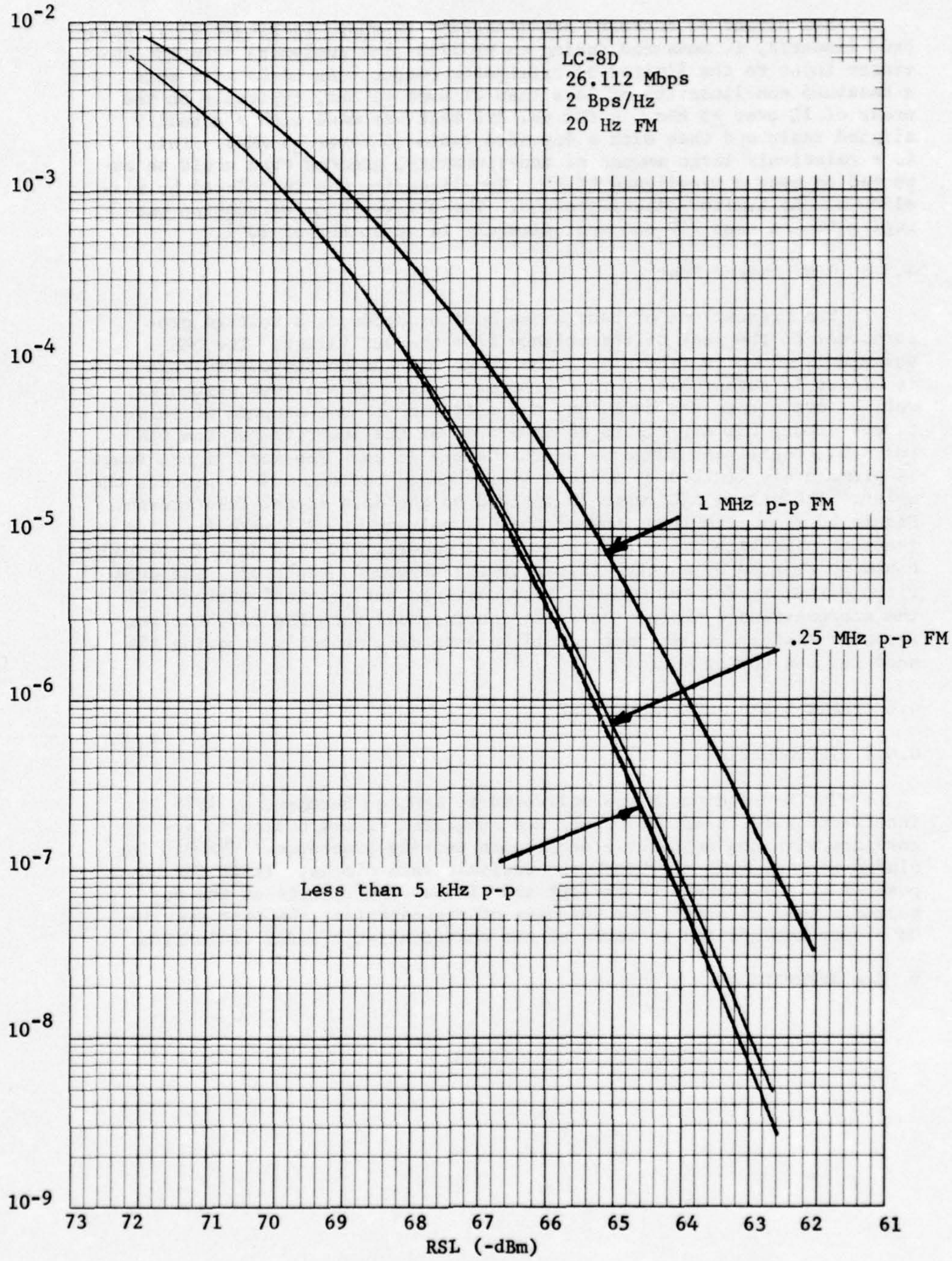


Figure 43
BER vs RSL vs BASEBAND NON-LINEARITY

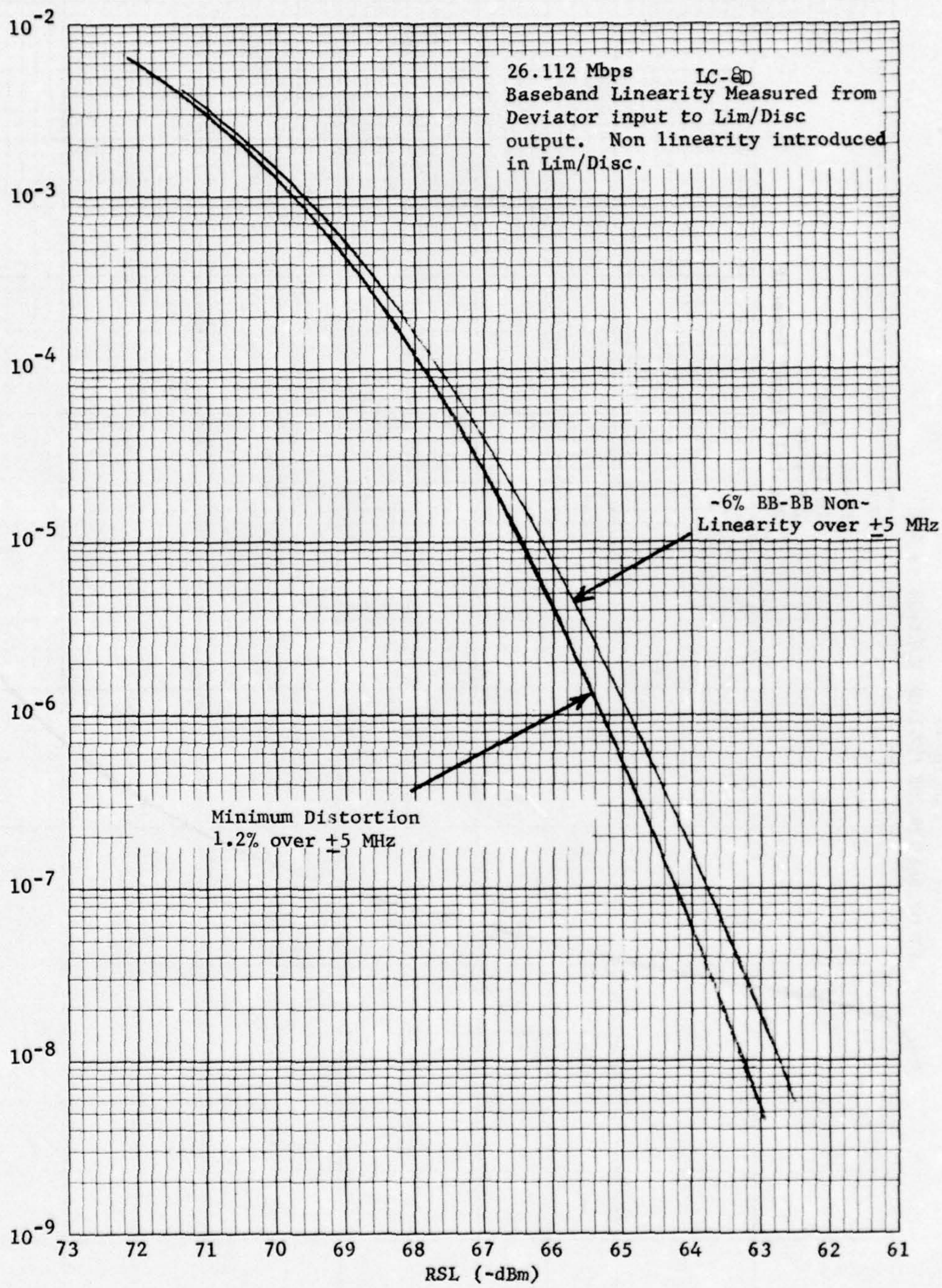


Figure 44
OUT OF BAND NOISE MONITOR VOLTAGE vs RSL

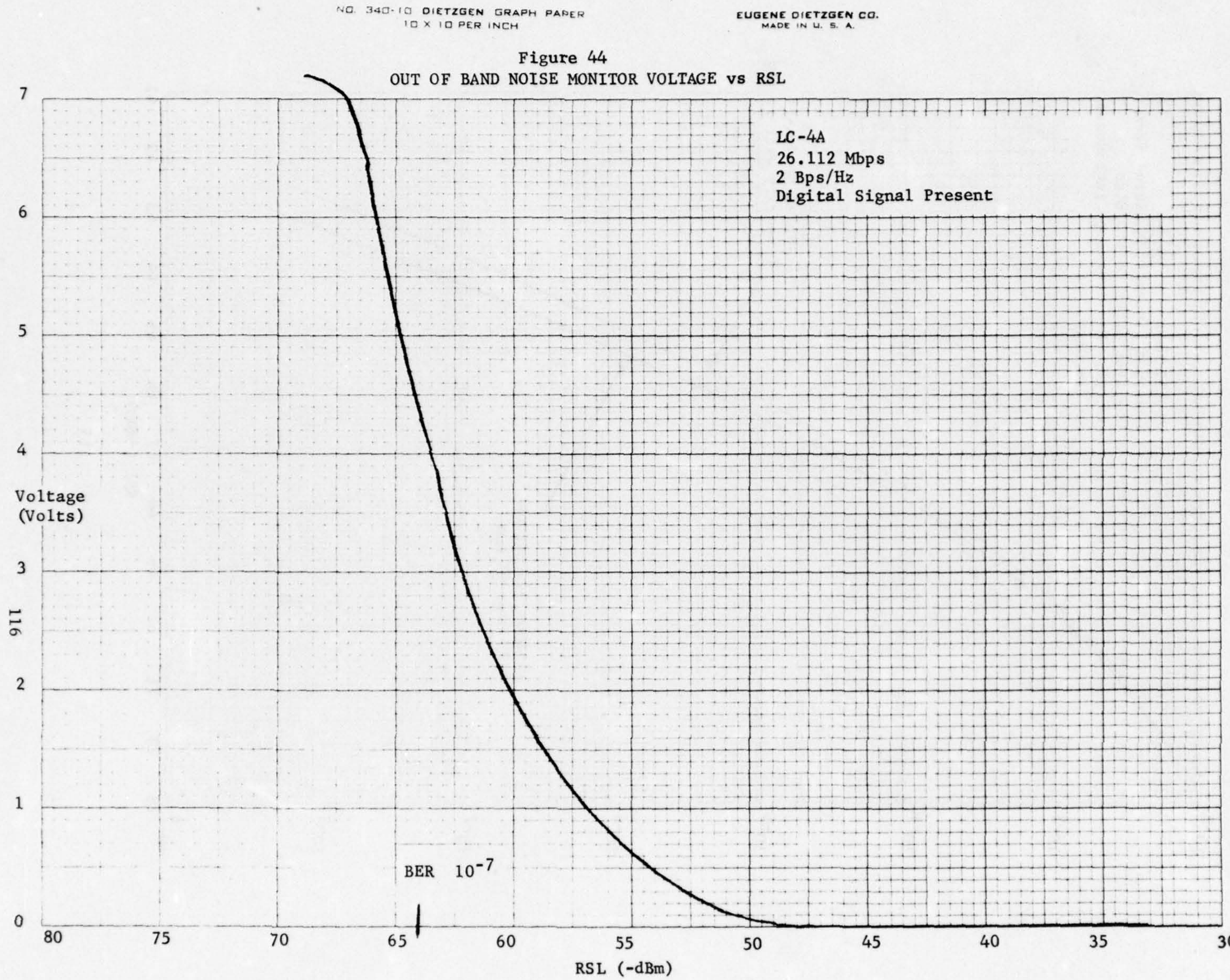


Figure 45. Log_{10} (OBN Voltage) vs. RSL

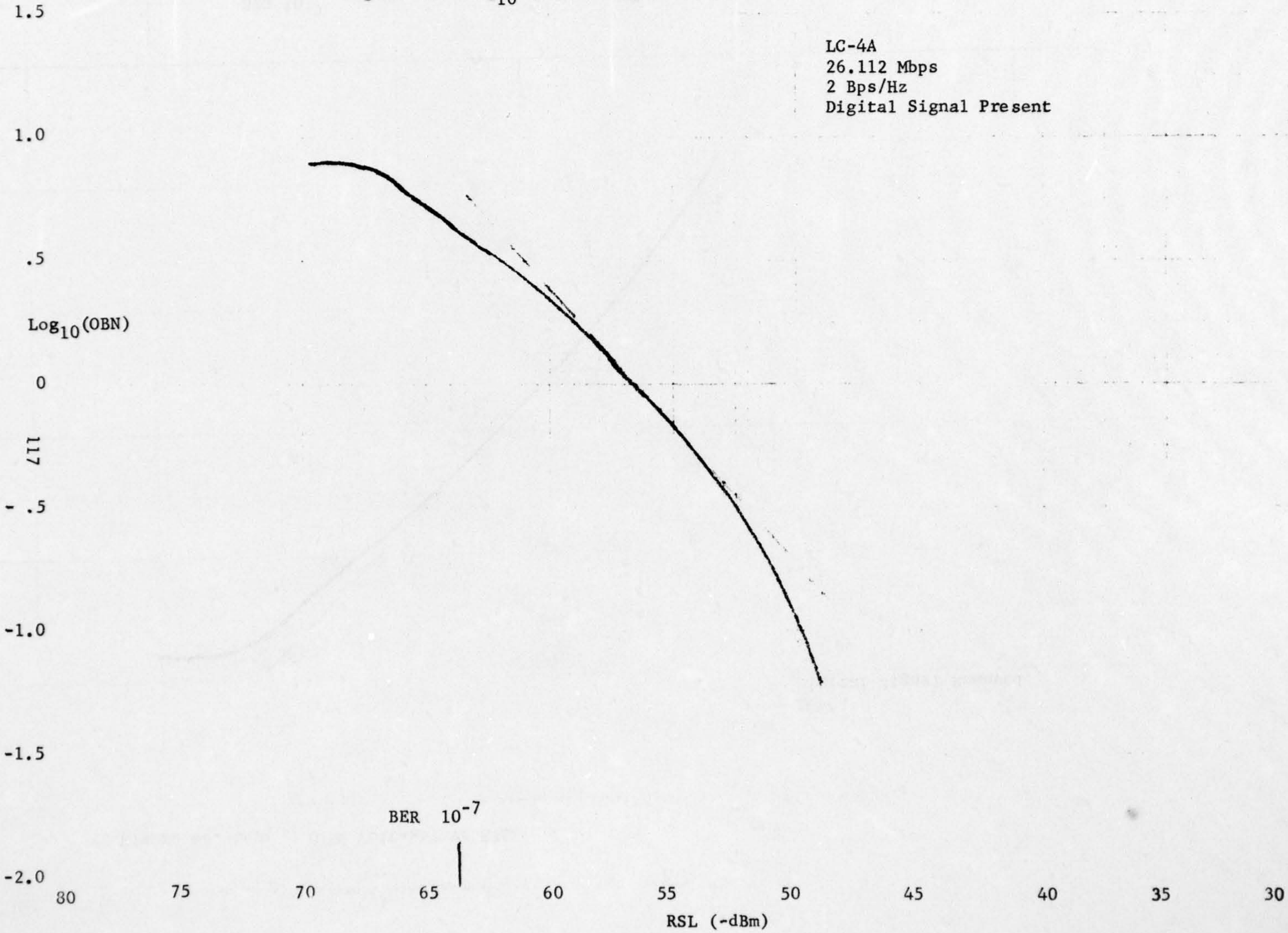
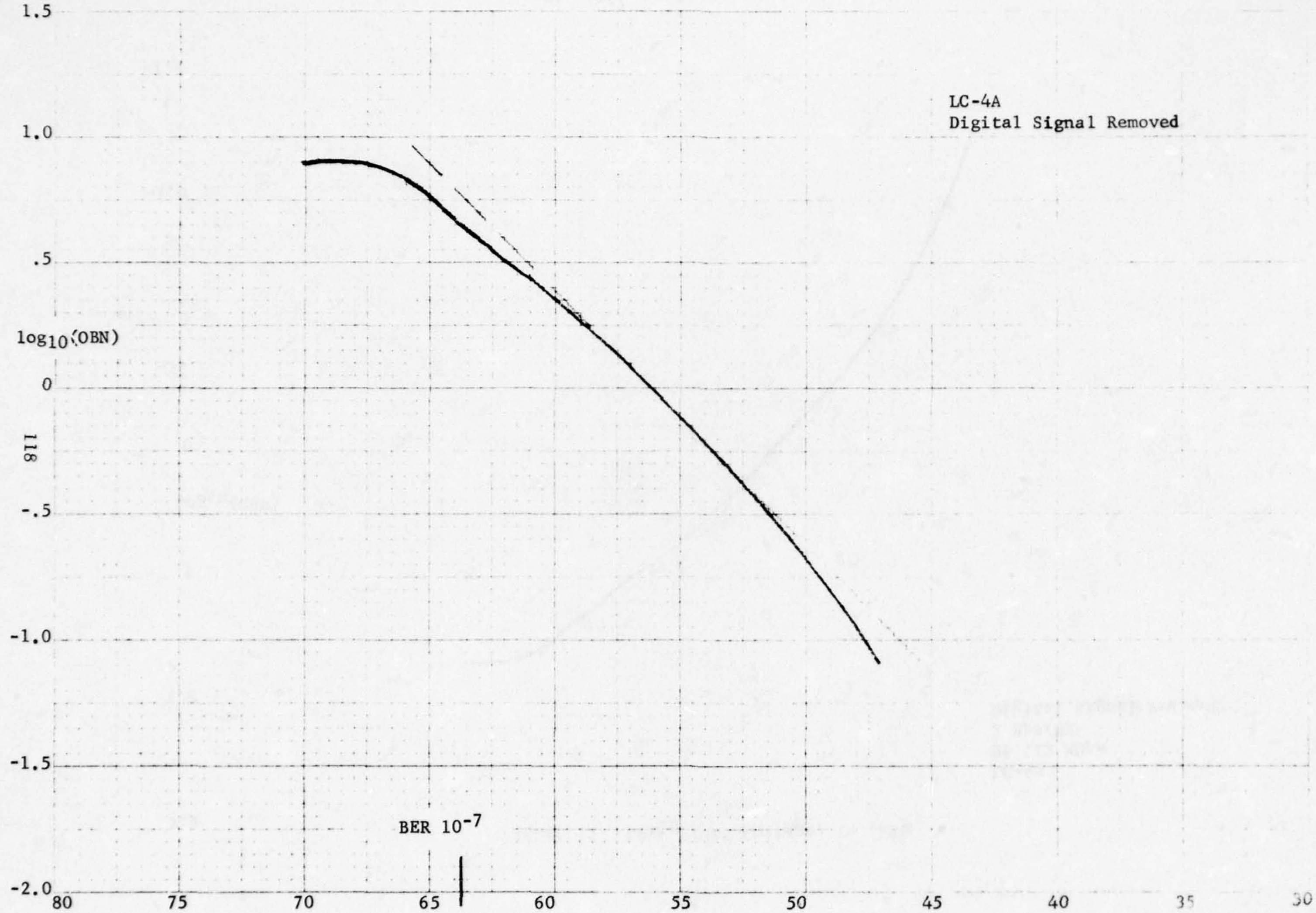


Figure 46. Log_{10} (OBN Voltage) vs RSL



4.6.2 Bit Error Rate vs. Received Signal Level

BER vs. RSL was taken for several values of IF filter bandwidth ** for MBS rates of 3.168, 9.504, and 12.672 Mbps (with MBS rate multiplier values of both 1 and 2) plus SCBS. In the proposed FRC-163 digital radio specification(6), the concept of 1 Bps/Hz and 2 Bps/Hz is replaced (paragraph 3.2.1.2.2) by performance levels which are based on assigned bandwidths. Table 13 shows the assigned bandwidths for various data rates. Performance levels I and II are very close to 1 Bps/Hz and 2 Bps/Hz.*

TABLE 13 . TRANSMITTED BANDWIDTHS

Total MBS Rate	Performance Level I	Performance Level II
3.168 Mbps	3.5 MHz	
6.336 Mbps	7.0 MHz	3.5 MHz
9.504 Mbps	10.5 MHz	7.0 MHz
12.672 Mbps	14.0 MHz	7.0 MHz
19.008 Mbps		10.5 MHz
25.344 Mbps		14.0 MHz

Figure 47 illustrates the BER vs. RSL results for 2 x 12.672 Mbps, performance level II. The transmission rate was 27.648 Mbps. These measurements were taken with the multiplexer MBS input data scrambler "OFF" and the scrambler at the MBS-SCBS multiplex output "ON". Therefore, the design goal of BER of 10^{-7} at 2 Bps/Hz for 2 x 12.672 Mbps becomes 3×10^{-7}. The results shown are 1.1 dB better than this. The BER for the service channel and both mission bit streams are essentially identical.

Figures 48A and 48B illustrate BER vs. RSL for 1 x 12.672 Mbps, performance levels II and I, respectively. At performance level II, the results are somewhat improved by a receiver IF filter narrower than 25 MHz. A BER of 3×10^{-7} is achieved at an E_b/N_o of 23.2 dB with a 15 MHz IF filter. At performance level I, the BER results are strongly dependent on the IF filter. A BER of 3×10^{-7} is achieved at an E_b/N_o of 15.3 dB with a 15 MHz IF filter.

---

(6) "Specification for Radio Set, AN/FRC-163", USACEEIA, Ft. Huachuca, AZ, 22 Apr 75.

* Except that for 9.504 Mbps and Performance Level II the transmission efficiency is very close to 1.5 Bps/Hz.

** See APPENDIX A

Figure 47

BIT ERROR RATE VS RECEIVED SIGNAL LEVEL

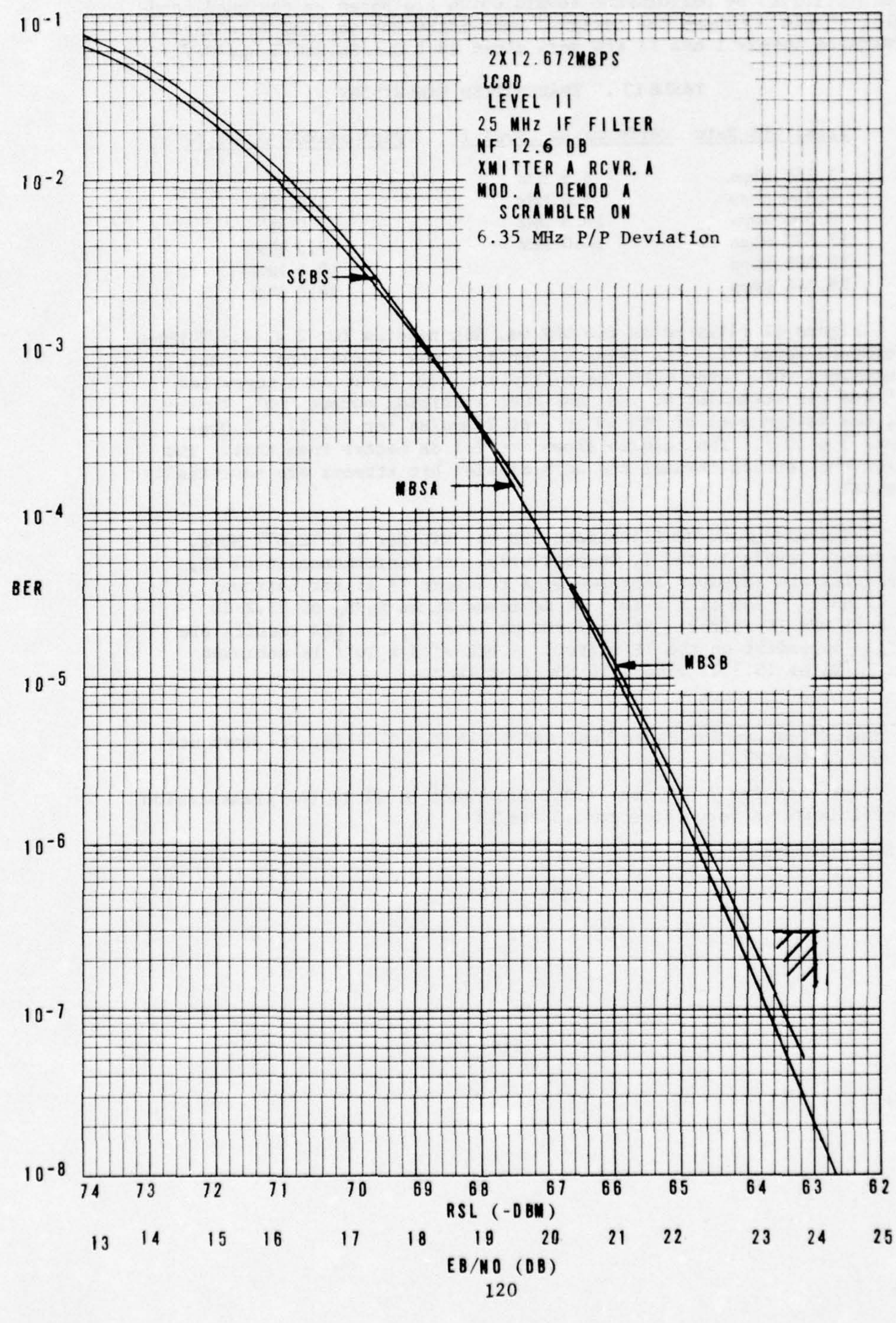


Figure 48-A

BIT ERROR RATE VS RECEIVED SIGNAL LEVEL

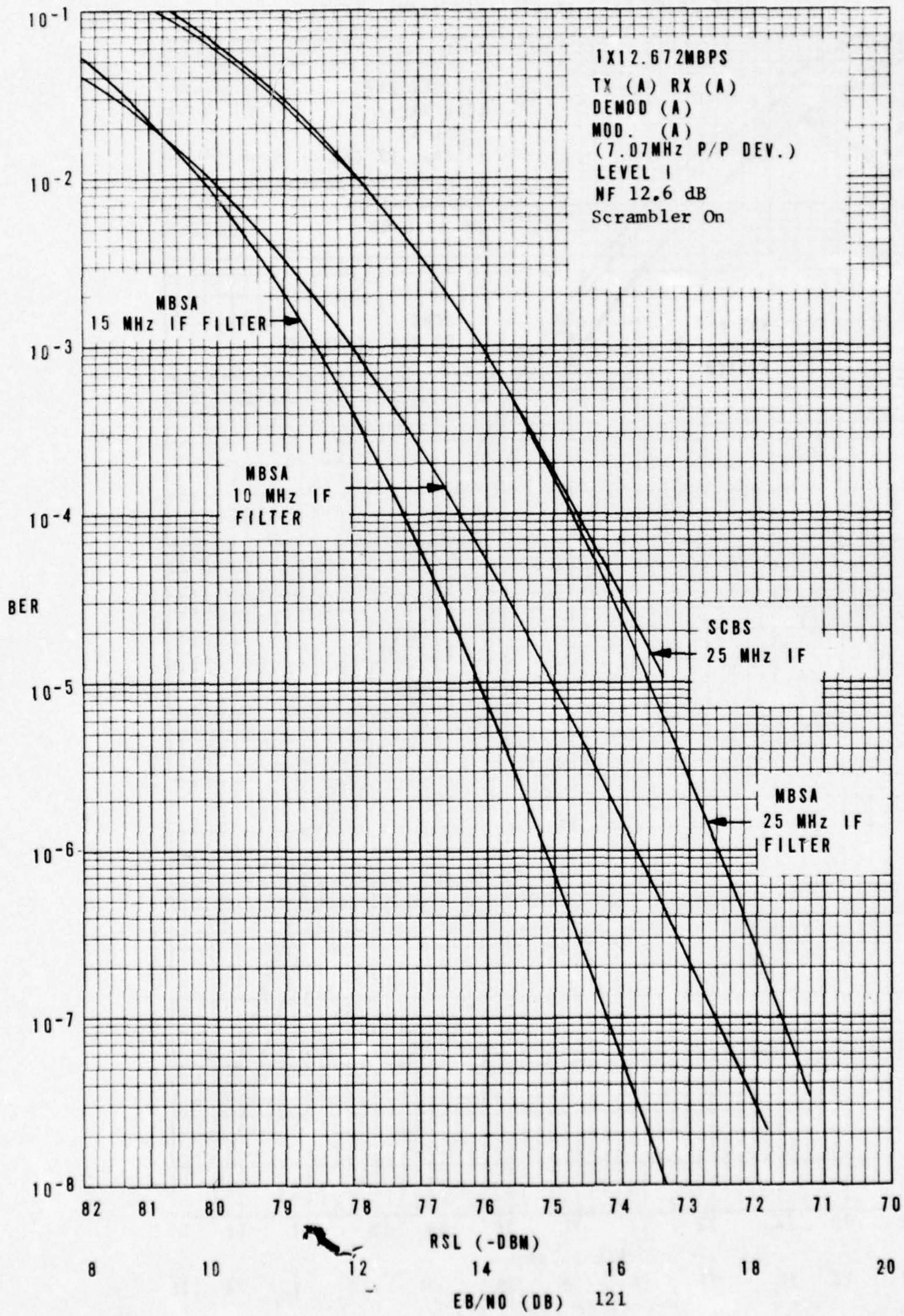
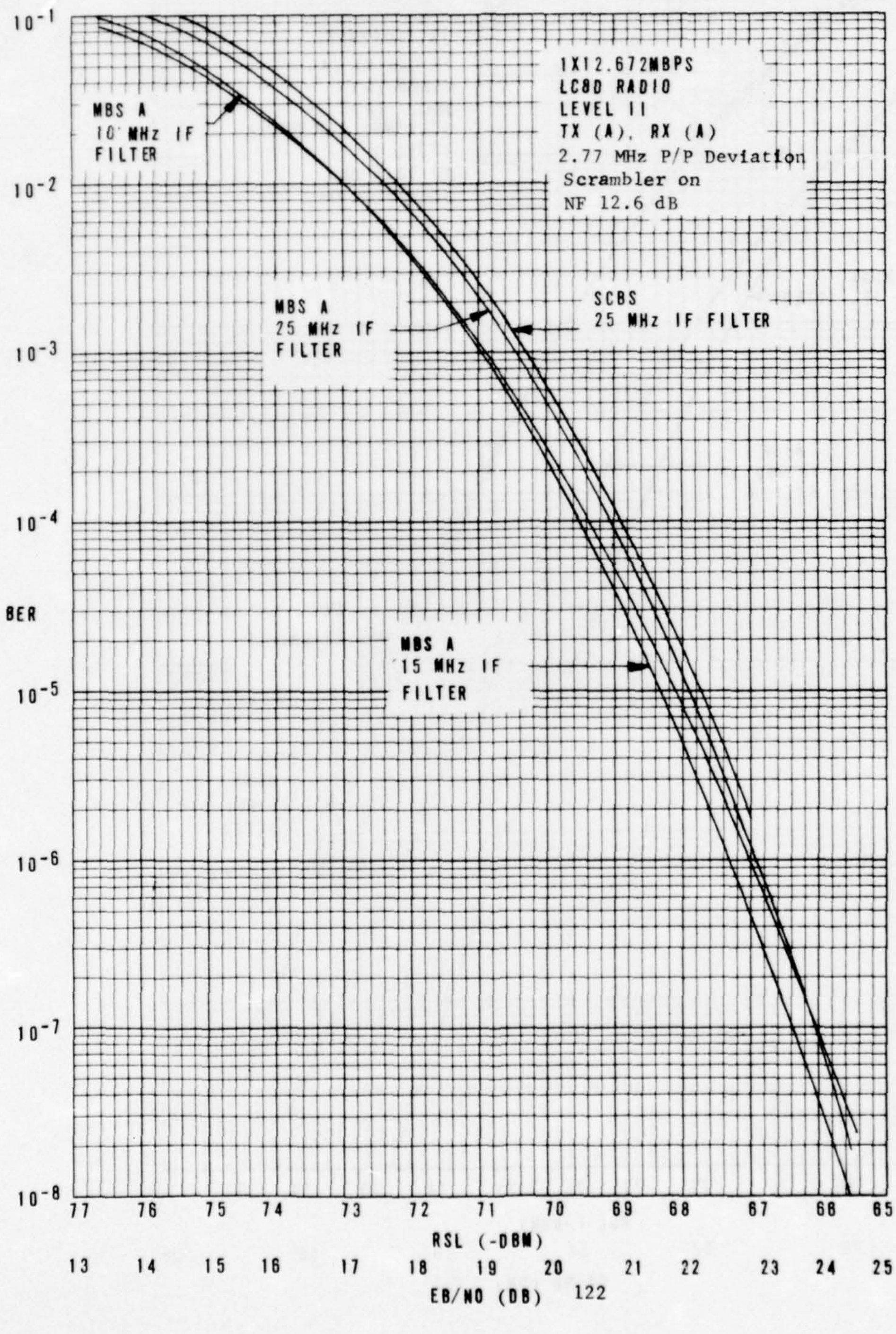


Figure 48-B

BIT ERROR RATE VS RECEIVED SIGNAL LEVEL



Figures 49 and 50 illustrate the results for 3.168 Mbps, X1 and X2, for IF bandwidths of 7 to 25 MHz. Figures 51, 52 and 53 illustrate the results for 9.504 Mbps, X1 and X2, for bandwidths of 10 to 25 MHz.

On Figure 49, note the small improvement given by the 7 MHz IF filter bandwidth, compared to the 10 MHz filter bandwidth. The same effect is seen in Figure 51 for the 10- and 15-MHz filter. On Figure 52, the 10 MHz filter results are inferior to those for the 15 MHz filter for Performance Level I, clearly showing that the optimum bandwidth is close to 15 MHz. The close grouping of the curves on this figure for Performance Level II indicated that the BER vs. RSL performance was essentially independent of the IF bandwidths used for these tests. This behavior is to be expected since the spectral components of significant energy content are well within the passband characterized by the narrowness of the filters employed.

4.6.3 Distortion Characteristics

The distortion of the LC-8D microwave radio was measured. The result is illustrated in Figure 54A . When parabolic delay distortion is added, the result is as given in Figure 54B. When negative or positive linear delay distortion is added, the result is as presented in Figure 55.

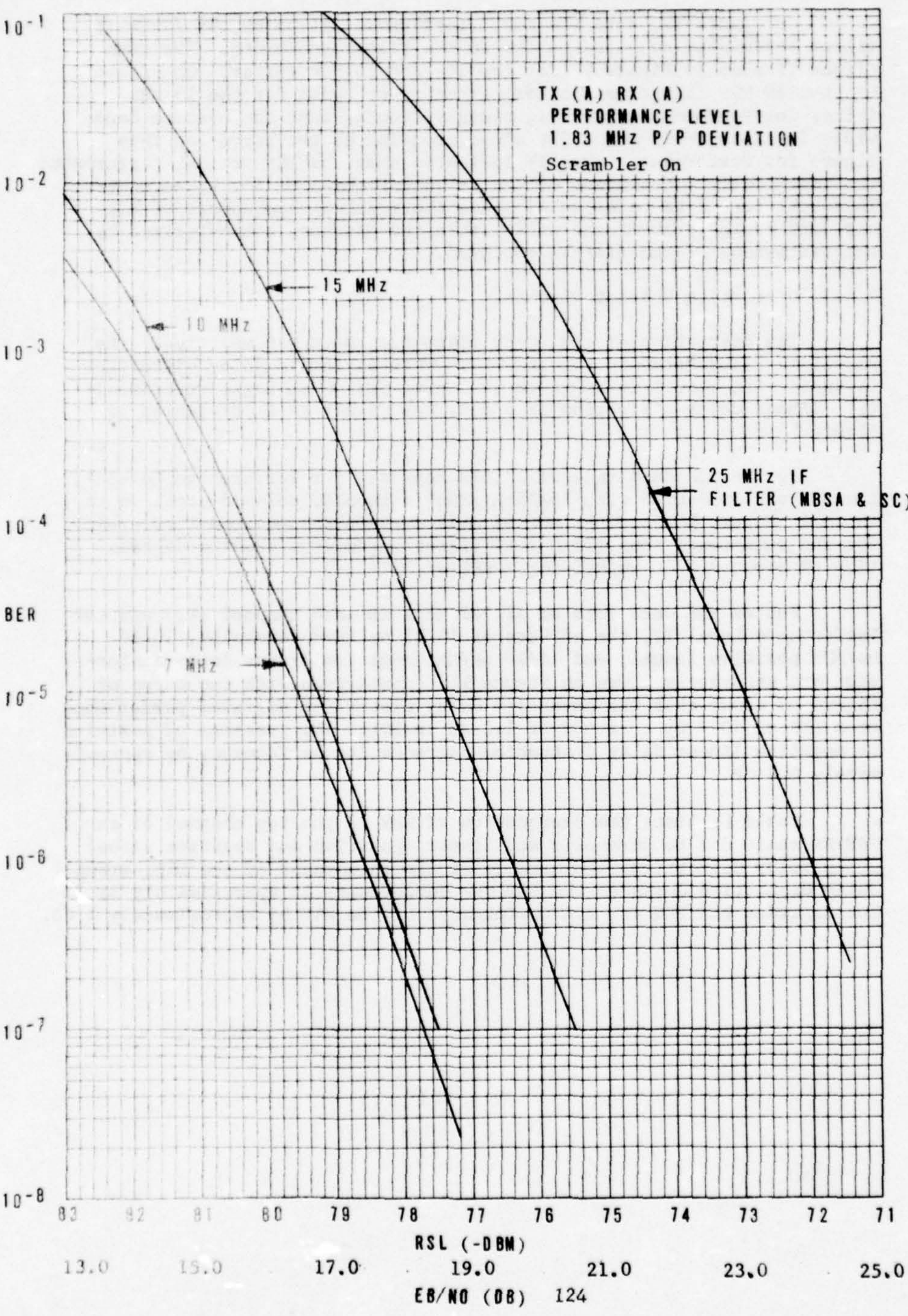
For an MBS data rate of 12.672 Mbps and for Performance Level I, the BER vs. RSL curve with 16/25 ns/MHz^2 parabolic delay distortion is shown in Figure 56. Comparison of this curve with one from Figure 48 A for the same conditions (25 MHz IF filter bandwidth) shows a degradation of about 0.4 dB in RSL for a BER of 10^{-7}.

For an MBS data rate of 12.672 Mbps in each channel (X2) and for Performance Level II, the effects of 16/25 ns/MHz^2 parabolic, 16/10 ns/MHz positive linear, and 16/10 ns/MHz negative linear delay distortion are separately given on Figure 57. Comparison with the curve of Figure 47 shows that the parabolic delay distortion degrades performance at a BER of 10^{-7} by a factor of 1.2 dB in RSL. The presence of positive or negative linear delay distortion degrades the performance by approximately 0.8 dB.

Table 14 lists the degradation of NPR in the top channel of an FDM-FM radio due to parabolic and linear (positive and negative slope) group delay distortion. An example of the robustness of the DAU, group delay distortion degrades the FDM NPR performance to approximately 38 dB but degrades the BER vs. RSL performance of the DAU by approximately 1 dB.

Figure 49

1 X 3.168 MBPS BER VS RSL



124

Figure 50-A

2X3.168MBPS BIT ERROR RATE VS RECEIVED SIGNAL LEVEL

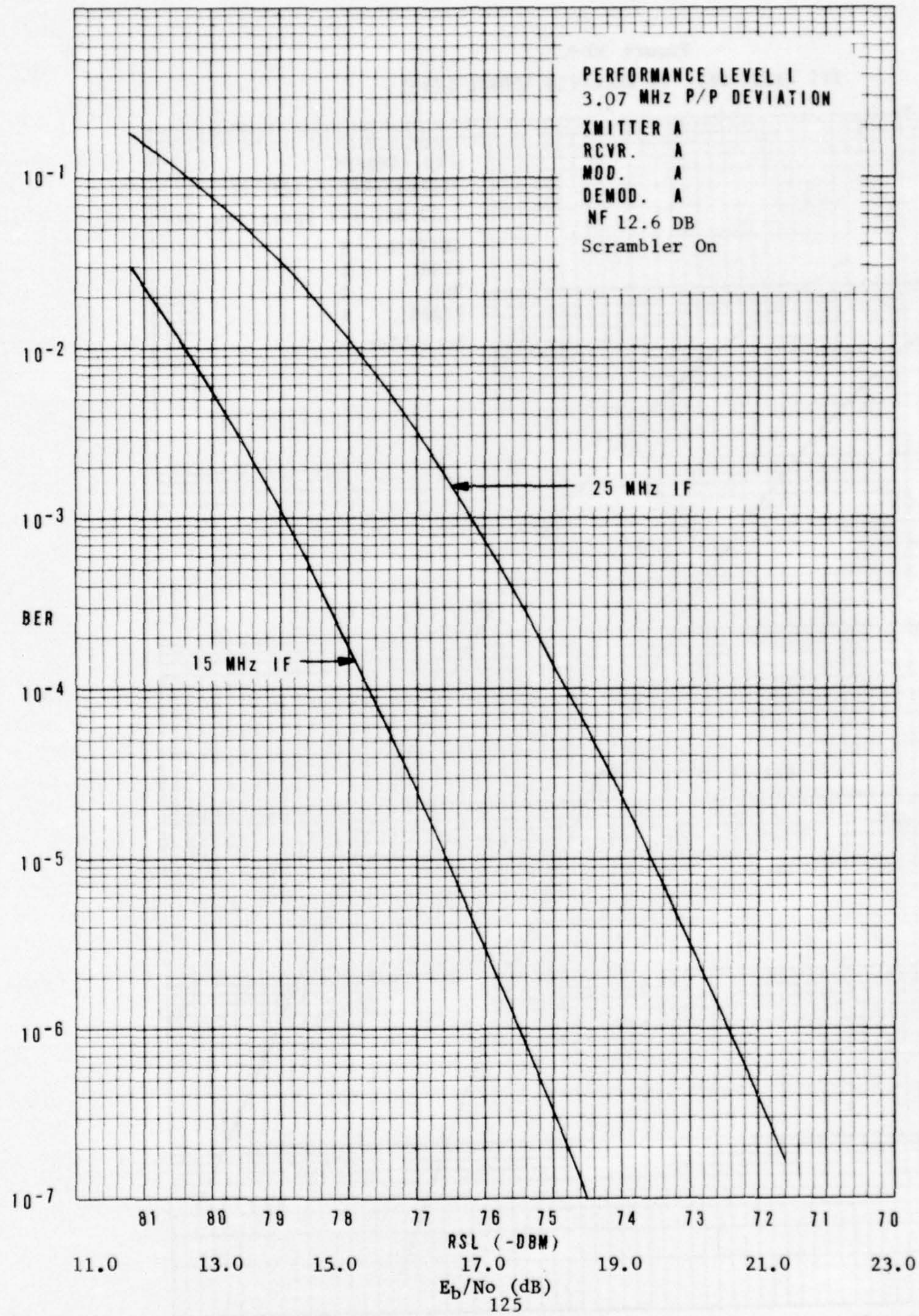


Figure 50-B

BIT ERROR RATE VS RECEIVED SIGNAL LEVEL

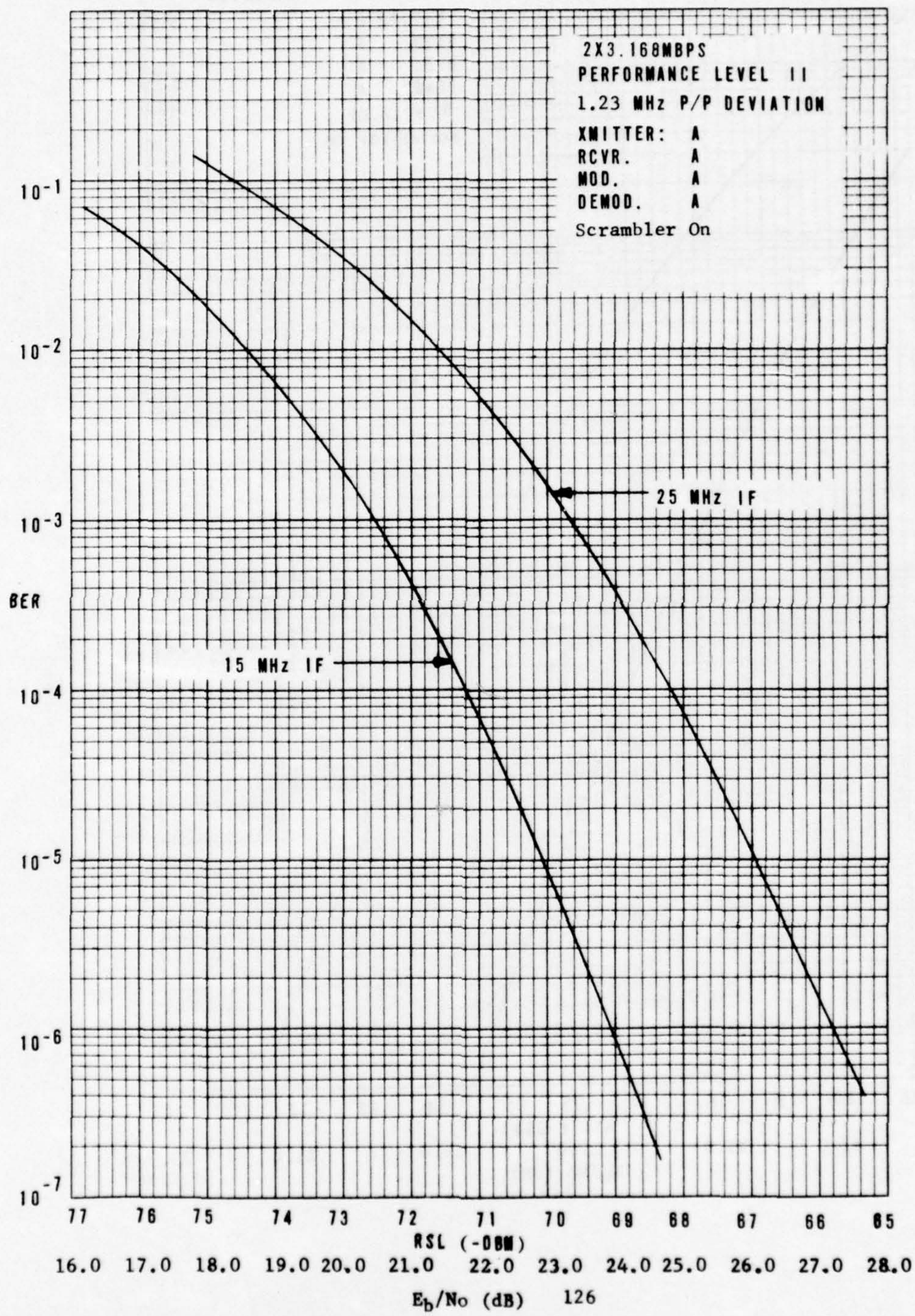
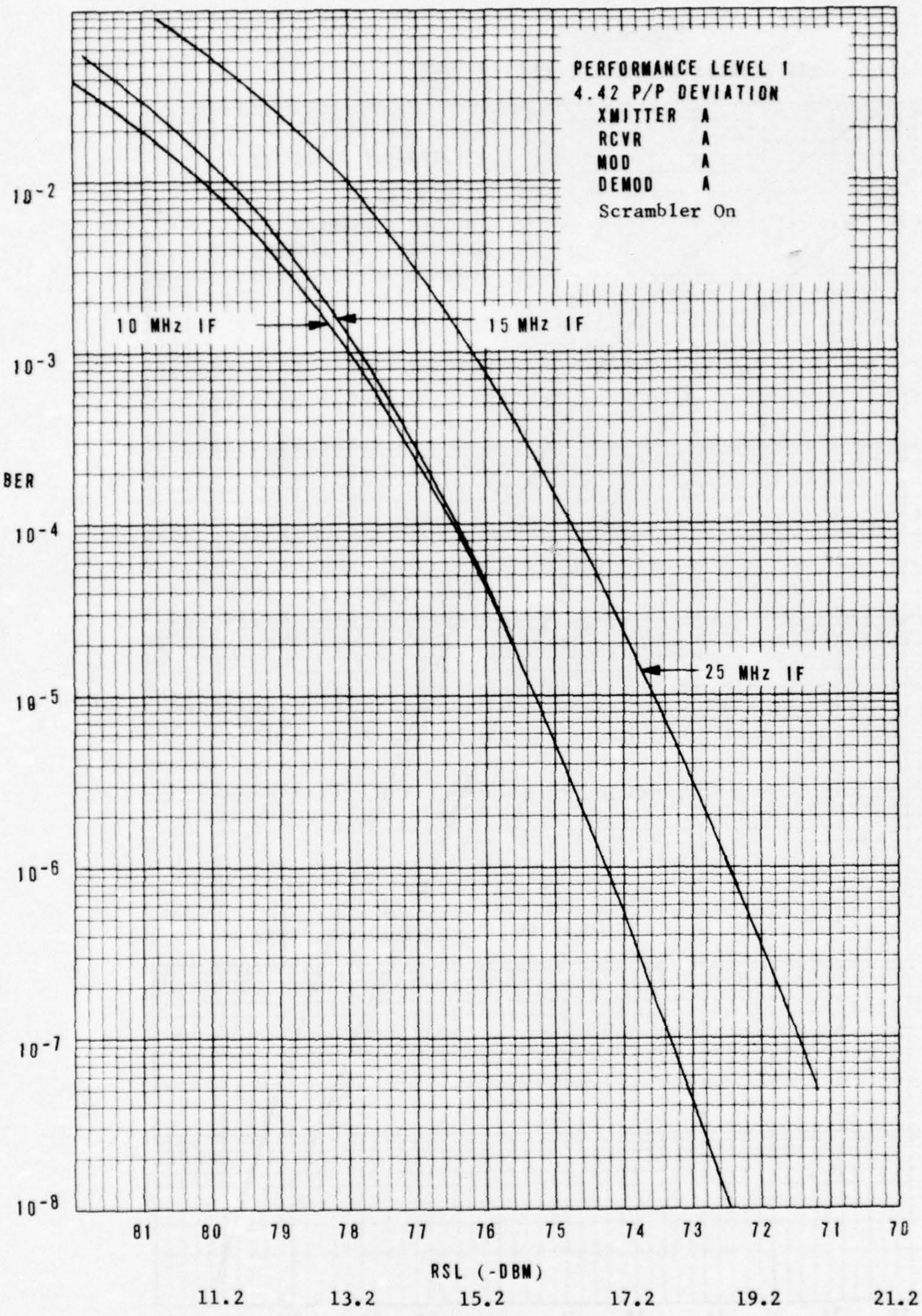


Figure 51

1X 9.504 MBPS BER VS RSL



127

Figure 52

1X9.504MBPS BER VS RSL VS IF FILTER

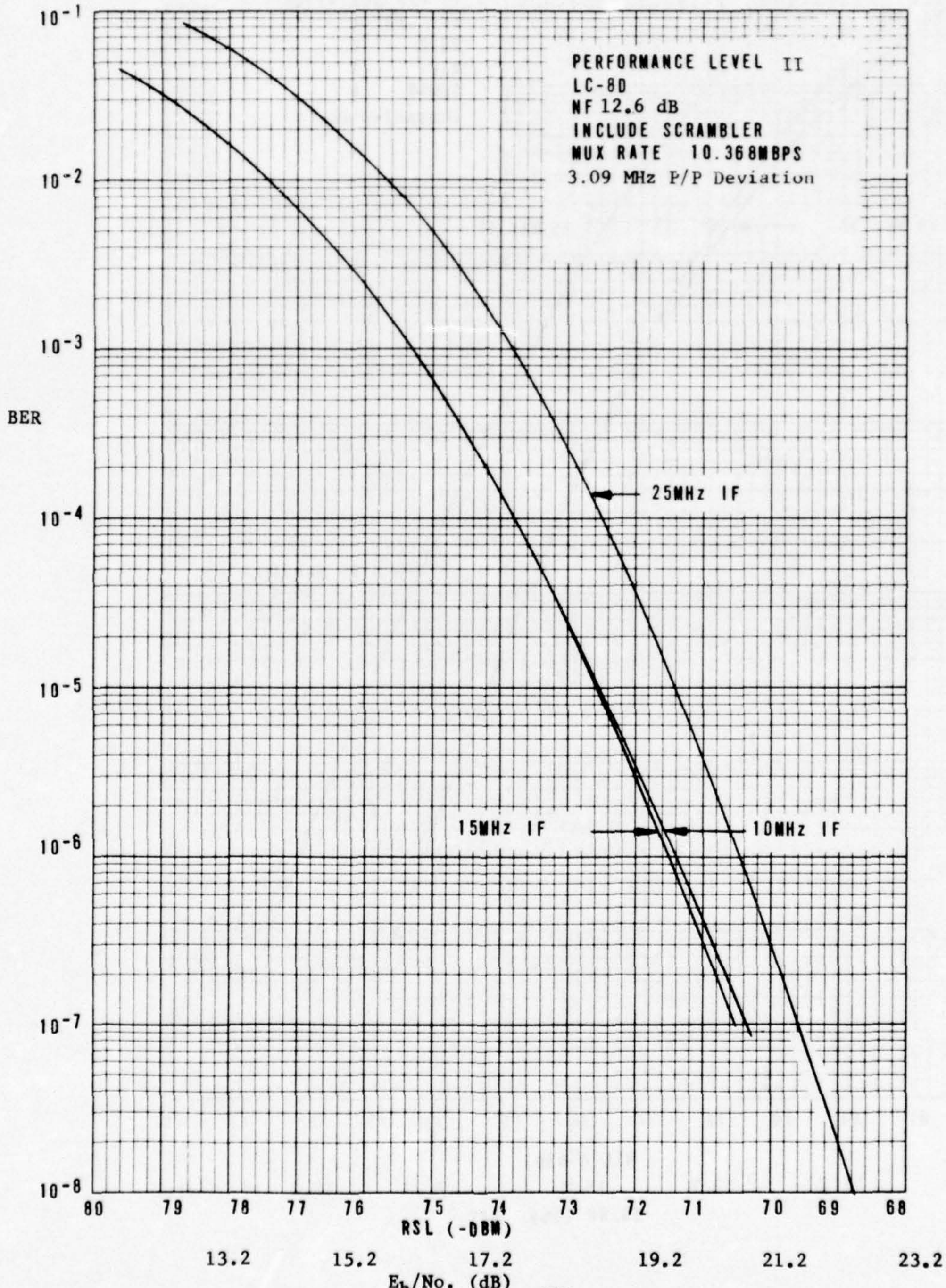


Figure 53

2X9.504MBPS BER VS RSL & IF FILTER

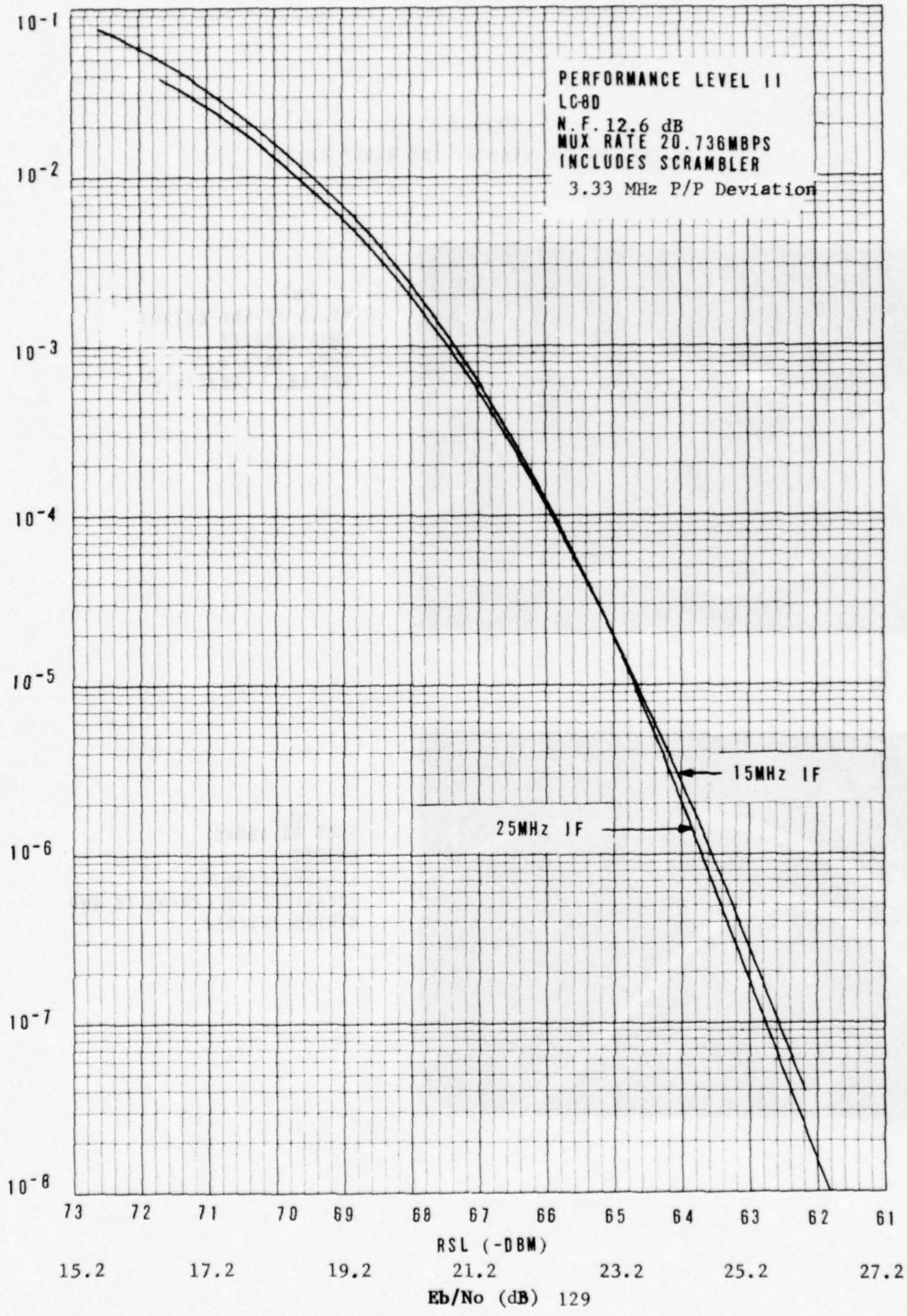
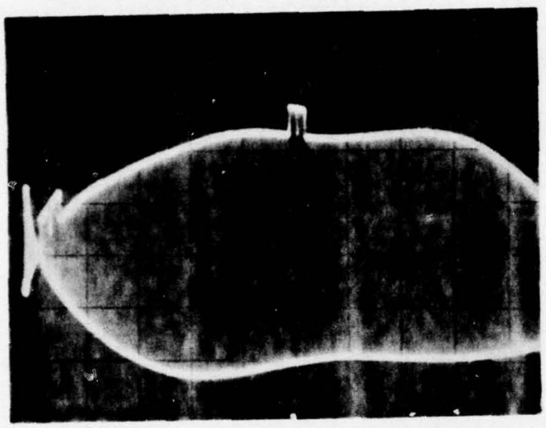
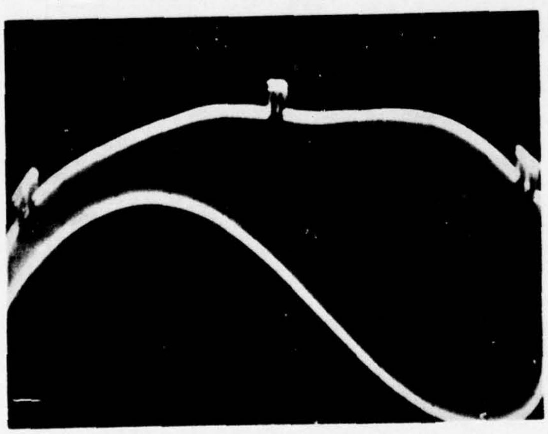


Figure 54

LC-8D RADIO LINEARITY AND GROUP DELAY

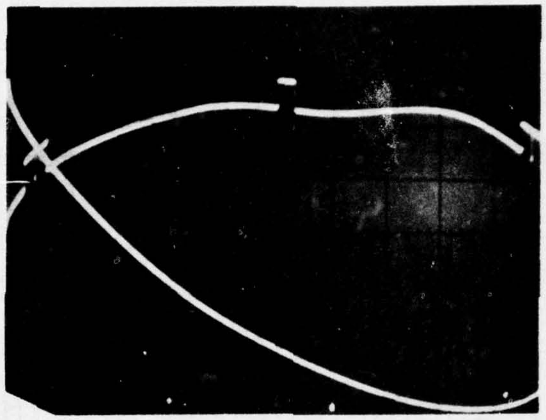


(a)
BB TO IF AMP OUTPUT
7MHz MARKERS
TOP: 1%/DIV
BOTTOM: 1NSEC/DIV



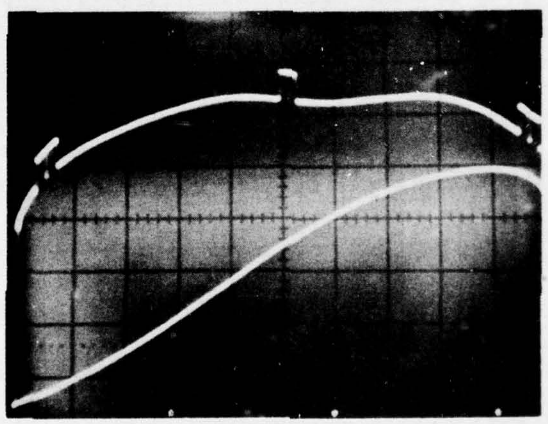
(b)
SAME AS ABOVE
EXCEPT
10/25NSEC/MHz^2
EQUALIZER FOLLOWING IF AMP
BOTTOM:3NS/DIV.

Figure 55
RADIO LINEARITY AND GROUP DELAY



(a)
LC-8D

BB TO IF
LINEAR GROUP DELAY
(-16/10NS/MHz)
EQUALIZER FOLLOWING
IF AMP
TOP: 1%/DIV.
BOTTOM 3NS/DIV
7MHz MARKERS



(b)

SAME AS ABOVE
EXCEPT
+16/10NS/MHz
LINEAR GROUP DELAY
EQUALIZER

Figure 56

1 X 12.672 MBPS BER VS RSL VS PARABOLIC GROUP DELAY DISTORTION

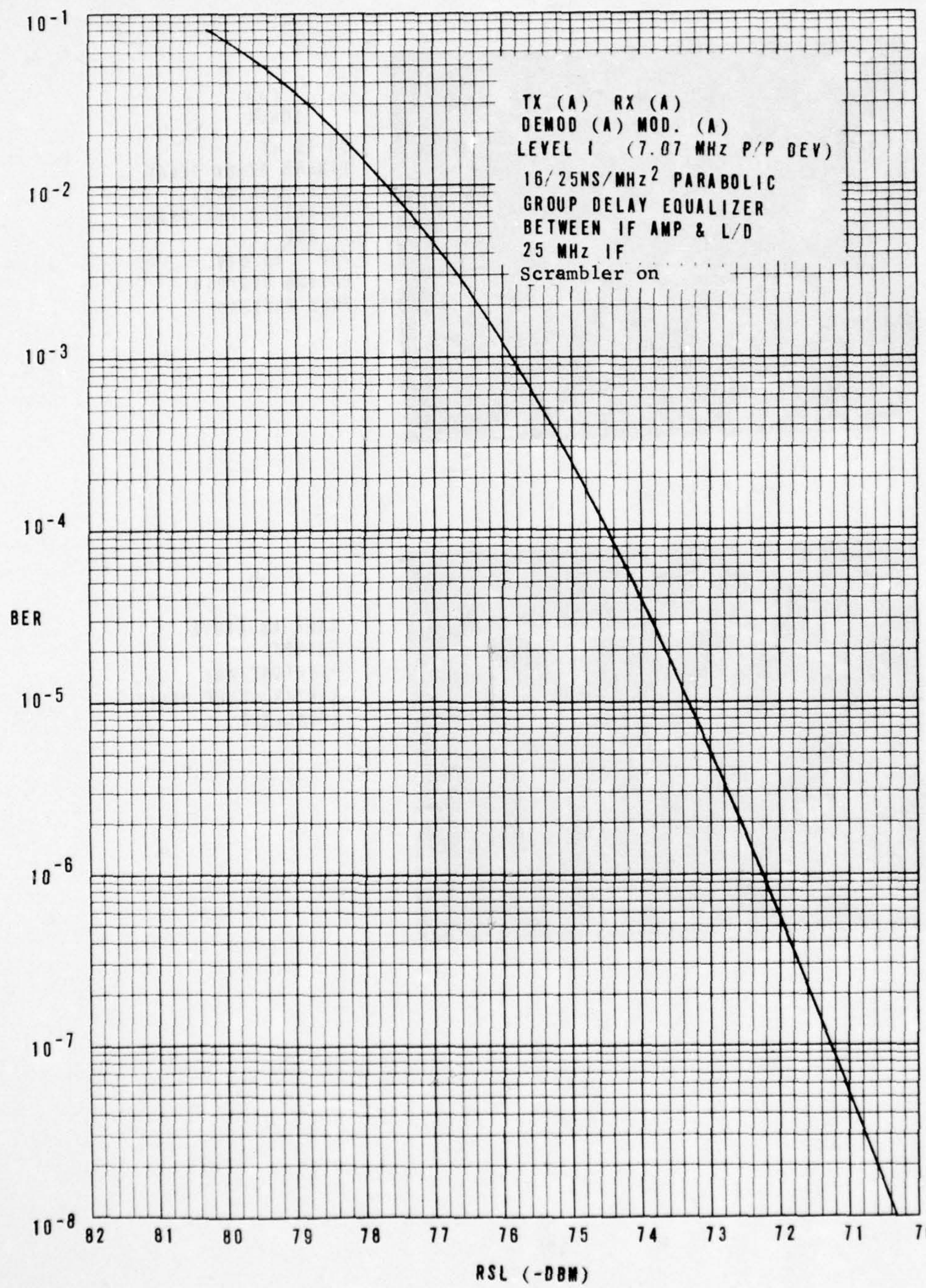


Figure 57

2X12.672MBPS BER VS RSL VS GROUP DELAY DISTORTION

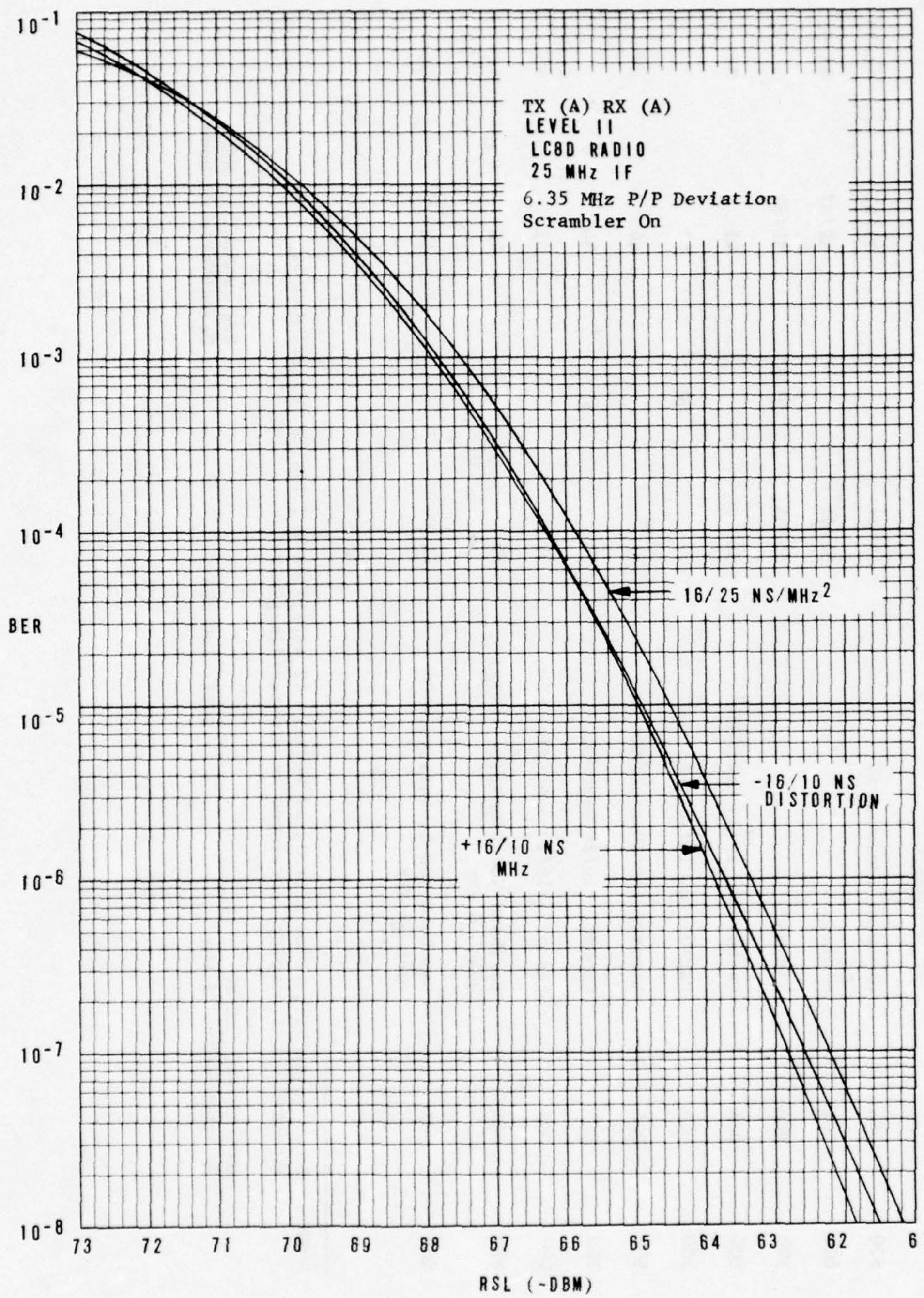


TABLE 14 NPR VS. RADIO DEGRADATION

CHANNEL CAPACITY	STANDARD	TYPE OF DISTORTION	NPR/BINR 70 kHz	534 kHz	1248 kHz	2438 kHz
600	DCA	Minimum, Mod-Demod Only (RF By-passed)	54/69		54/65	56/57
600	DCA	Minimum, Includes RF	54/66		51/63	46/56
600	CCIR	Minimum	54/61		52/57	48/51
300	DCA	Minimum	55/64	53/67	52/62	
600	DCA	Parabolic, 16/25 nsec/MHz^2	56		41	37
300	DCA	Parabolic, 16/25 nsec/MHz^2	57	50	43	
600	DCA	Linear, +16/10 nsec/MHz	51		44	39
300	DCA	Linear, +16/10 nsec/MHz	52	51	46	
600	DCA	Linear, -16/10 nsec/MHz	52		42	38
600	DCA	Baseband Non-Linearity, -6% over $\pm$6 MHz	52		49	47
600	DCA	Baseband Non-Linearity, -10% over $\pm$6 MHz	44		44	45

NOTES: Group delay distortion introduced between IF amplifier and limiter/discriminator
Baseband non-linearity introduced in limiter/discriminator

Radio Type: LC-8D
IF Bandwidth: 25 MHz
SCTT: 140 kHz
Pre-emphasis: None
De-emphasis: None

In accordance with the DAU alignment procedure each of the baseband filters (transmit and receive) is adjusted to provide a nominal 3 dB of attenuation to the Nyquist frequency of the symboling rate. If the baseband to baseband frequency response of the interfacing microwave radio equipment is sufficiently broad, the frequency response of the decoder input waveform will be of the raised cosine type, as determined by the characteristics of the baseband filters of the DAU. A restricted baseband to baseband frequency response of the microwave radio equipment will alter the frequency response of the decoder input waveform and cause a degradation in the error rate performance of the system. In order to determine the degree of degradation caused by a restricted microwave radio baseband response a 3 section unequalized Butterworth Filter was inserted between the radio receiver output and the Baseband Demodulator input. The filter was adjusted to provide 0, -1 and -2 dB of attenuation at the Nyquist frequency of the symboling rate, and the resultant error rate vs. RSL was recorded. The data obtained is presented in Figure 58. As can be noted in the figure at a BER of 10^{-8} a degradation of approximately 4 dB is encountered for 2 dB of attenuation at the Nyquist frequency above and beyond that introduced by the baseband filters of the DAU. Most of this degradation can be compensated for, if it is deemed necessary, by readjusting the response of the DAU filter networks.

4.6.4 Eye Patterns

Since quality of the received eye pattern is indicative of the BER performance achievable, one facet of the testing effort was devoted to the recording and analysis of the eye patterns. Specifically, photographs were taken of the received eye pattern in an endeavor to determine the impact of varying IF bandwidth on the quality of the eye pattern. Eye patterns were photographed for total MBS rates of 3.456 Mbps, 12.672 Mbps and 25.354 Mbps.

Figure 59A is a photograph of the received eye pattern for the case of a dual 12.672 Mbps MBS, Performance Level II, and an IF bandwidth of 25 MHz. As can be noted in the figure, the closure of the eye pattern at the center of the eye is approximately 10 percent. This amount of eye closure is attributed to the presence of noise and some intersymbol distortion due to phase non-linearities of the pre- and post-detection filtering. Intersymbol distortion due to the presence of the 25 MHz IF filter appears to be of negligible magnitude.

Figure 59B is a photograph of the eye pattern taken for a single MBS input of 12.672 Mbps. The half power IF bandwidth for this measurement was 25 MHz and the bandwidth efficiency factor was set to Performance Level I. A peak eye closure of about 12 percent at the center of the eye is evident. This degree of eye closure is attributed to the presence of noise and some intersymbol distortion due to phase non-linearities in either the radio or the post-detection filtering.

Figure 58

BER VERSUS RSL VERSUS BASEBAND FREQUENCY RESPONSE

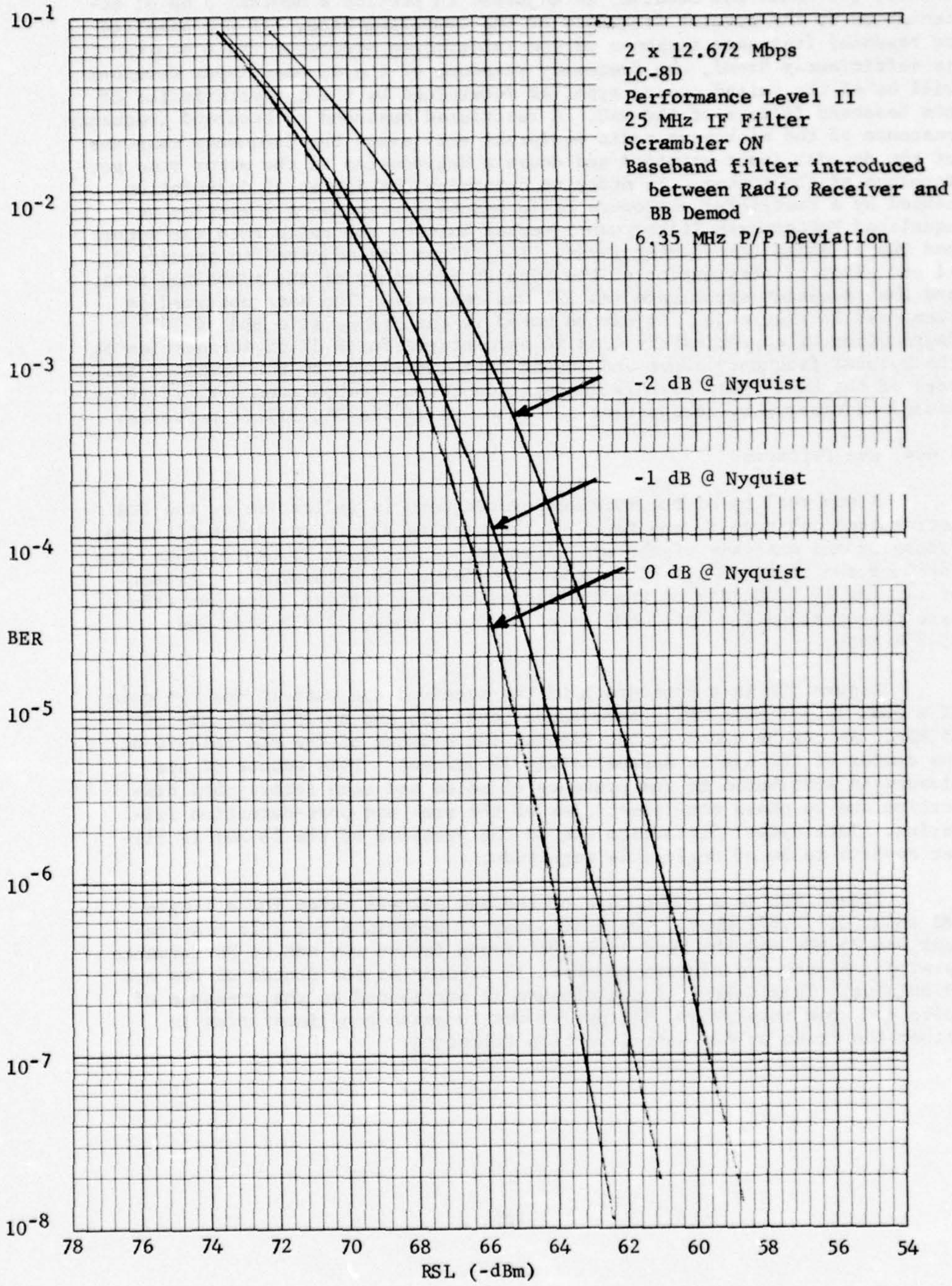
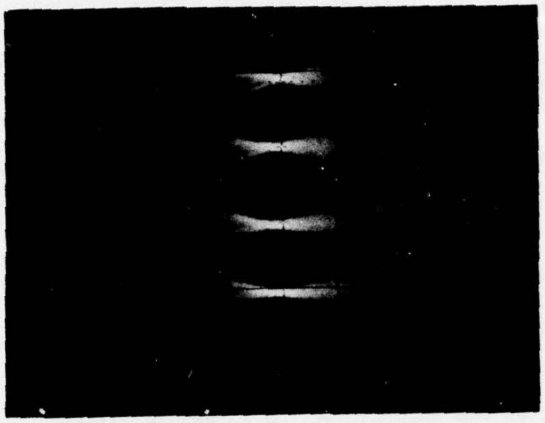
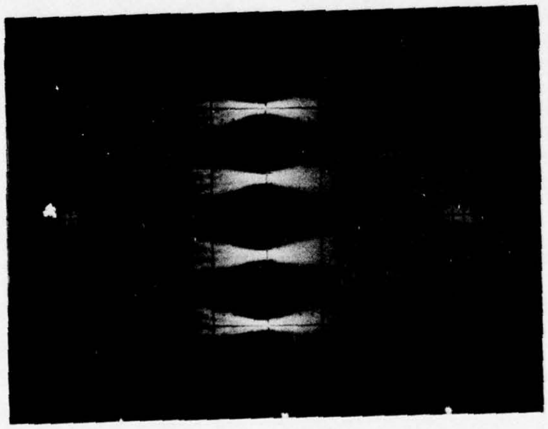


Figure 59
RECEIVED EYE PATTERN



(a)
2X12.672MBPS
50MV/DIV.
10NSEC/DIV.
25MHz IF FILTER
2BPS/Hz



(b)
1X12.672MBPS
50MV/DIV
20NSEC/DIV
25MHz IF FILTER
1BPS/Hz

Figure 60 is a photograph of the received eye pattern for the case of a single 12.672 Mbps MBS input, Performance Level II, and an IF bandwidth of 25 MHz. The test conditions for this eye pattern measurement are identical to those used for obtaining photograph Figure 59B except for the increased performance level, II instead of I. Referring to Figure 60, it is noted that the peak eye closure at the center of the eye is about 10 percent, which is slightly better than that obtained for Performance Level I. However, the difference is too small to draw any relevant conclusions as to the apparent cause of the improvement in the percent of eye closure for the Level II case as compared to the Level I case. The apparent reasons for the closure for the Level I eye pattern presented above apply equally well to the Level II case.

Figure 61 is a photograph of the received eye pattern for a single 12.672 Mbps input, Performance Level I, and a half power IF bandwidth of 10 MHz. Referring to the figure, it can be noted that the percentage of eye closure at the center of the eye is approximately 25. The partial eye closure, for this case, is attributed to intersymbol distortion which is generated as a result of the truncation of the spectral components of the received signal waveform due to the presence of the 10 MHz IF filter. It is apparent that an IF filter bandwidth of 10 MHz is not an optimum choice for the transmission of a 12.672 Mbps MBS.

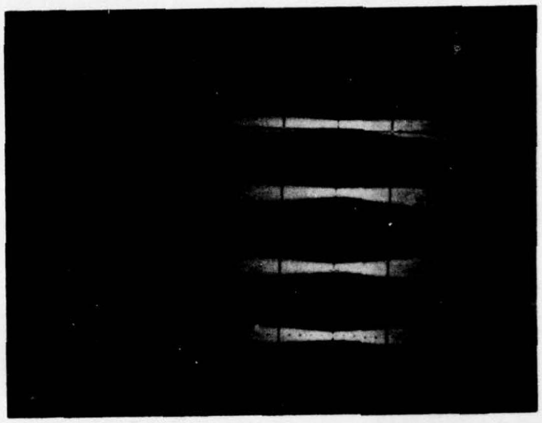
Figure 62 is a photograph of the received eye pattern for the case of a single 3.168 Mbps MBS input, Performance Level I, and a half power IF bandwidth of 7 MHz. The percentage of closure of the eye pattern at the center of the eye is on the order of 10 to 12, which is to be expected in consideration of the relatively wide IF bandwidth used for this measurement. The partial closure of the eye pattern is attributed to the presence of noise and some intersymbol distortion due to phase non-linearities of the post-detection filtering. Intersymbol distortion due to the presence of the 7 MHz IF filter appears to be of negligible magnitude.

4.6.5 Performance Monitor Meter Indication

Two analog indications of DAU performance (eye closure and out-of-band noise) are available, via switch selection, for meter display on each demodulator module. During the testing at RADC, these performance monitors were recorded for various combinations of data rate and bit packing density vs. RSL. Figures 63 through 68 inclusive are graphic presentations of the data collected.

Monitor circuit gains as well as the selection of the out-of-band noise filter were optimized for the highest data rate. The curves indicate that on subsequent programs the optimization of the monitoring circuit parameters should proceed on a per data rate basis as is the optimization of transmit and receive signal filtering.

Figure 60
RECEIVED EYE PATTERN

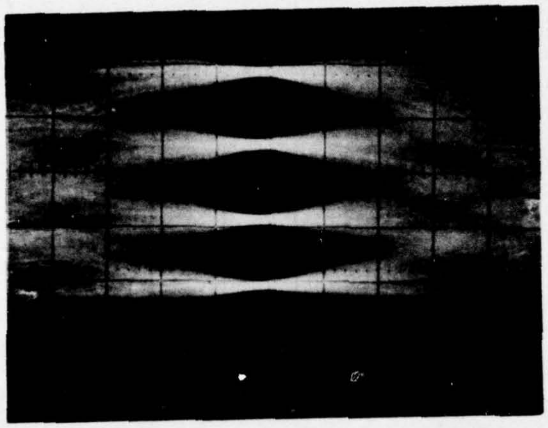


1X12.672MBPS
2BPS/Hz
25MHz IF

Figure 61
RECEIVED EYE PATTERN

1X12.672MBPS
50MV/DIV
20NSEC/DIV
10MHz IF FILTER
1BPS/Hz

Figure 62
RECEIVED EYE PATTERN



1X3.168MBPS
50NSEC/DIV
50MV/DIV
7MHz IF

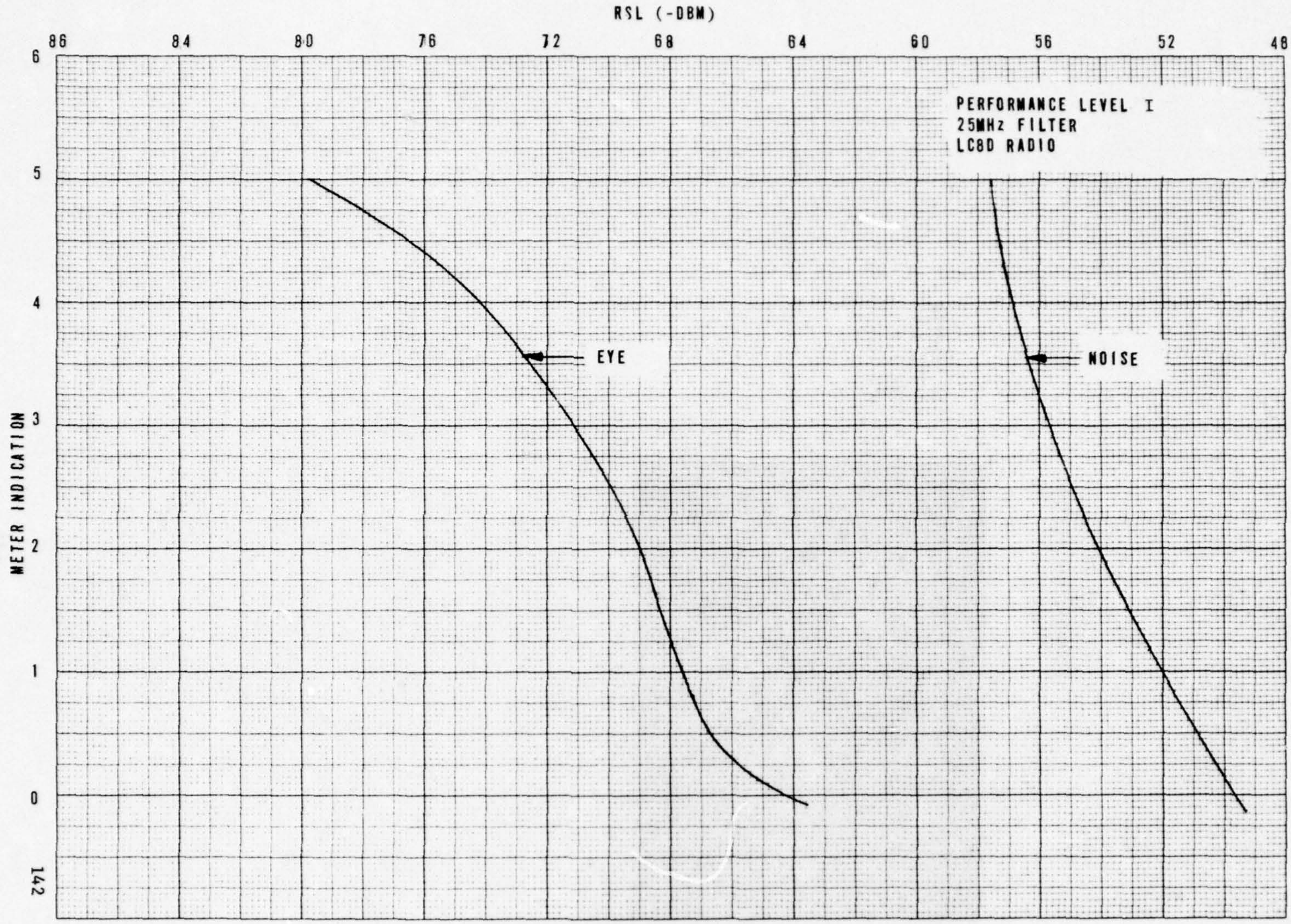


FIGURE 63

2X3.168MBPS PERFORMANCE ASSESSMENT METER INDICATION VS RSL

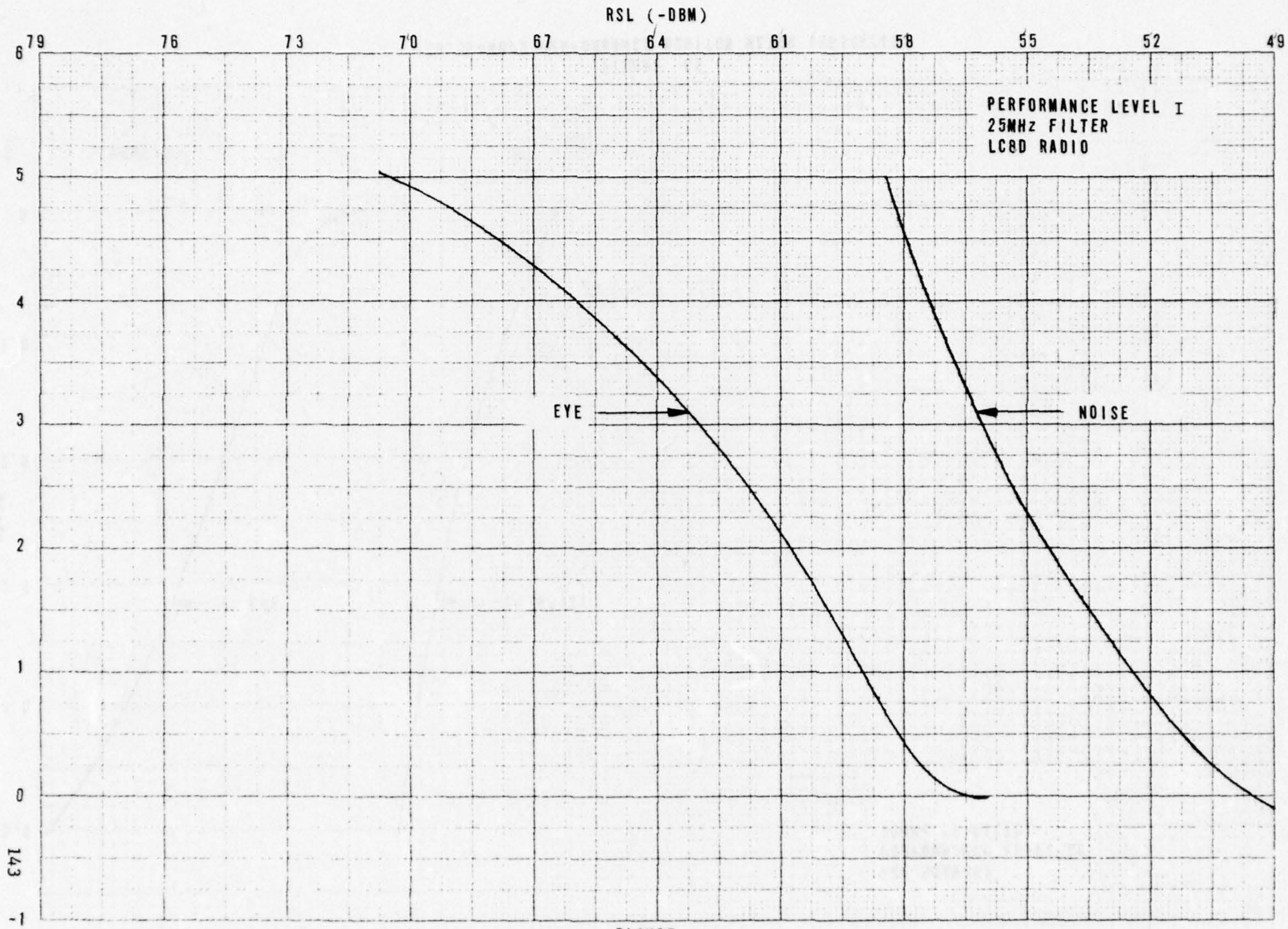


FIGURE 64

2X9.504MBPS PERFORMANCE ASSESSMENT METER INDICATION VS RSL

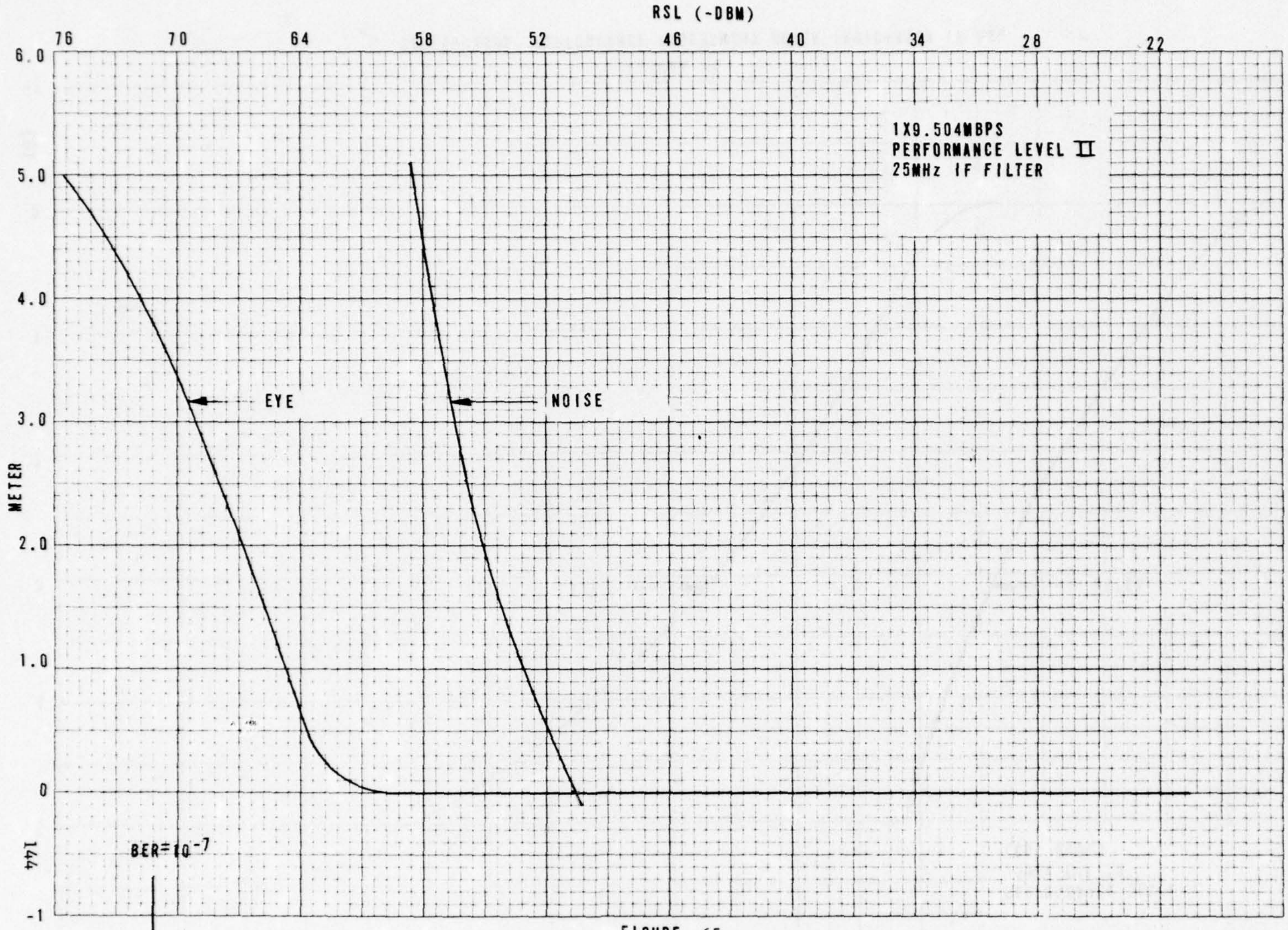


FIGURE 65
1X9.504MBPS PERFORMANCE MONITOR METER INDICATION

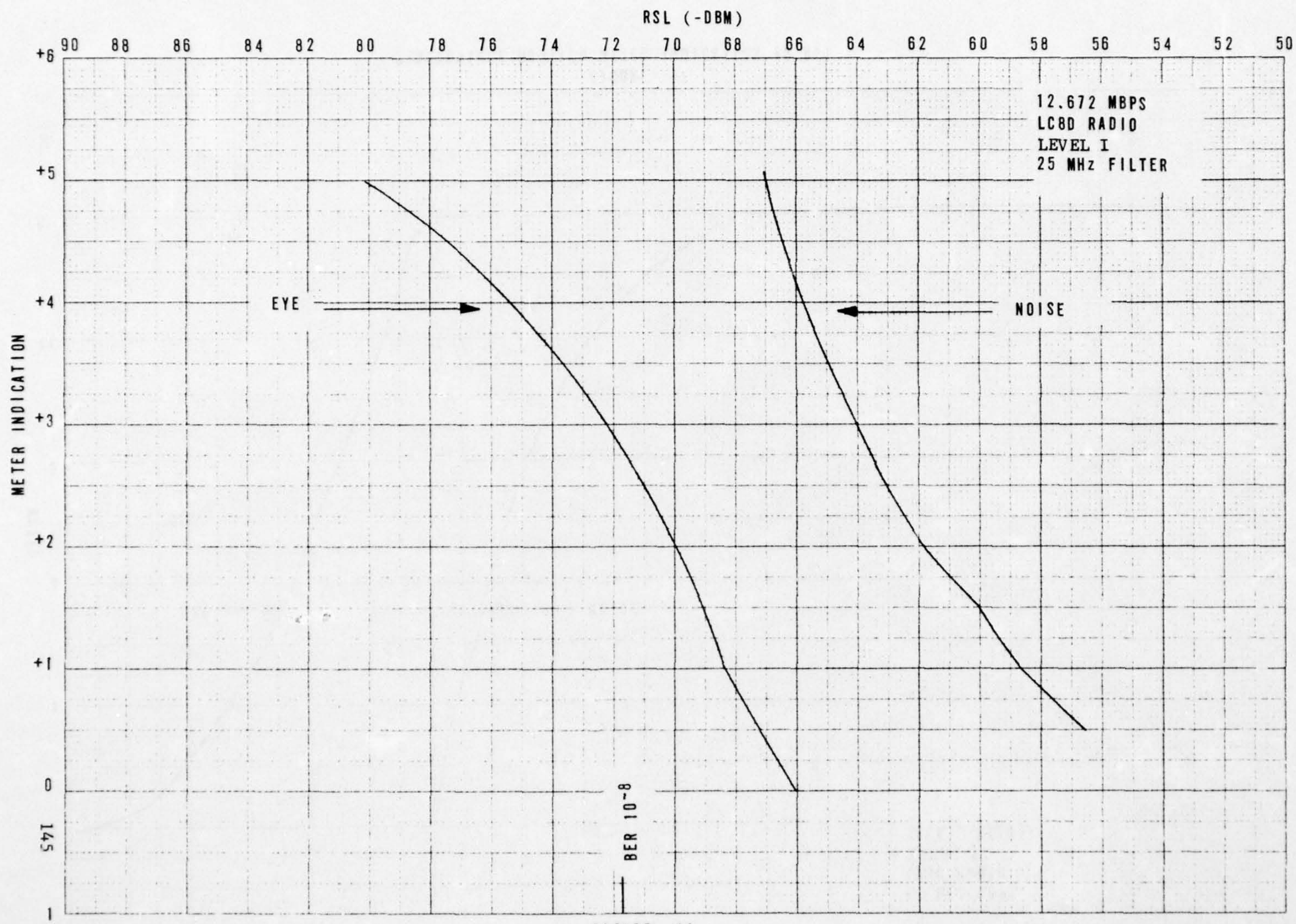


FIGURE 66
PERFORMANCE MONITOR METER INDICATION VS RSL

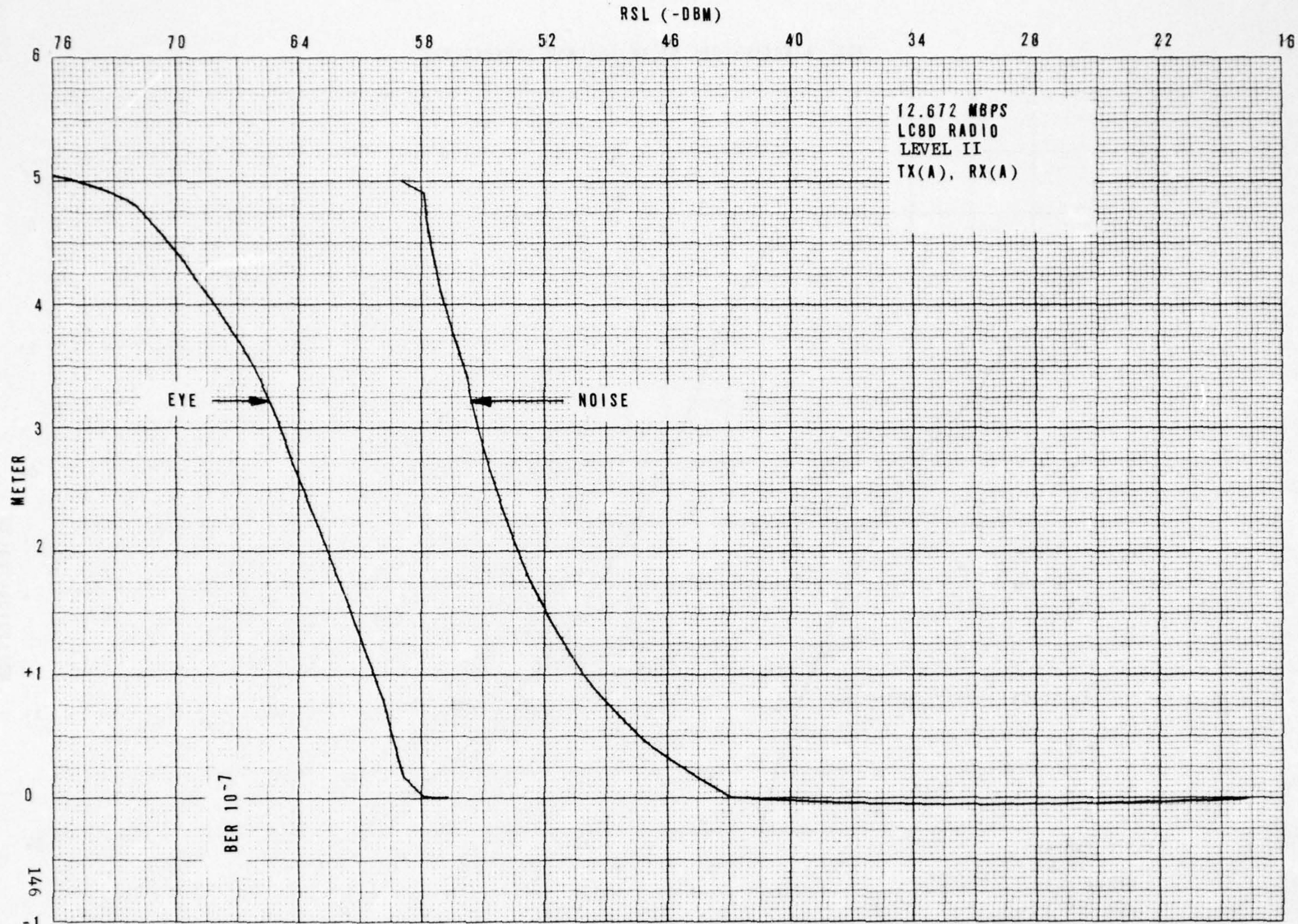


FIGURE 67
PERFORMANCE MONITOR METER INDICATION VS RSL

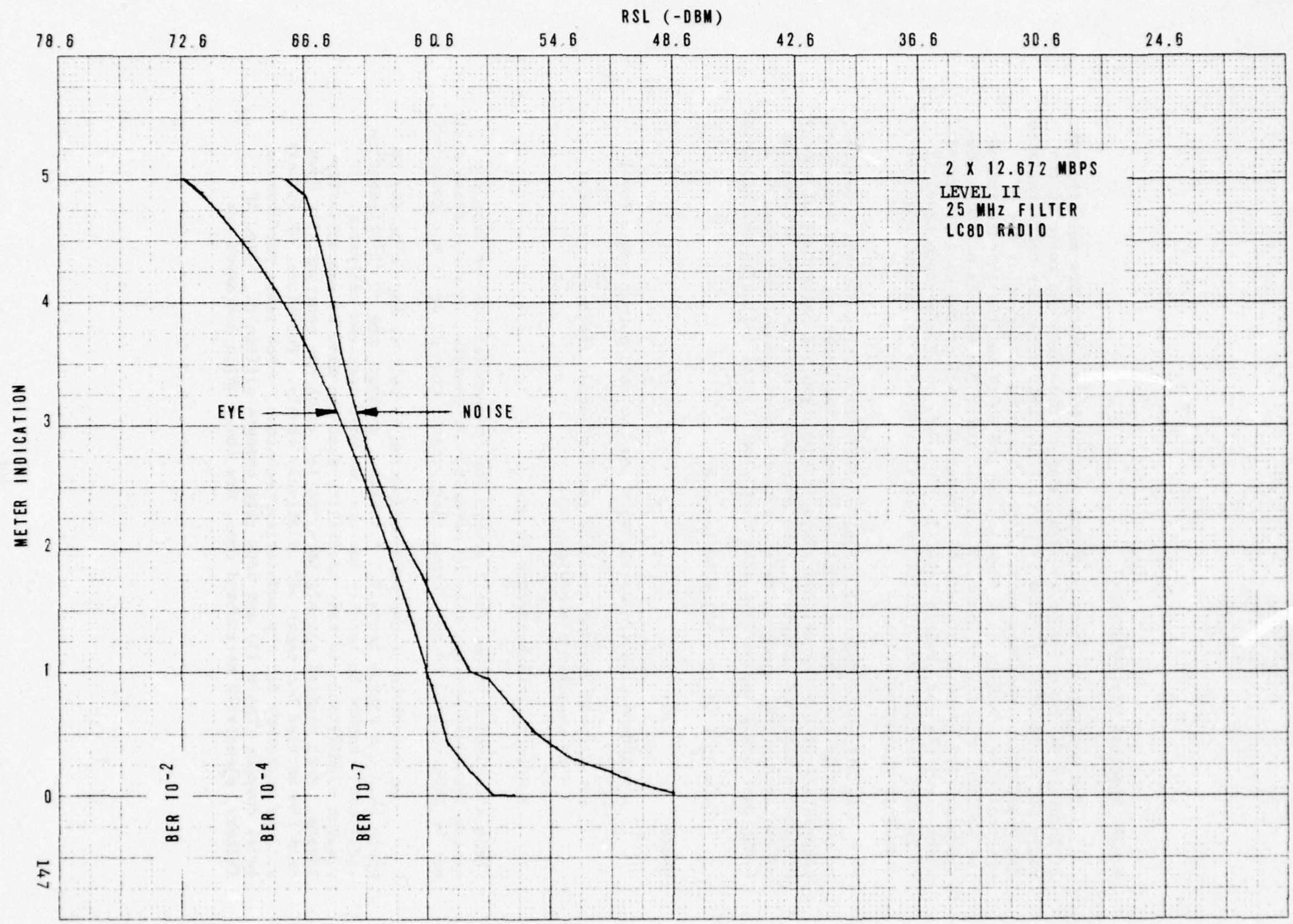


FIGURE 68
PERFORMANCE ASSESSMENT METER INDICATION VS RSL

4.6.6 Spectral Distribution

The evaluation tests performed on the DAU at each transmission rate of interest was preceded by an adjustment of the deviation ratio of the radio set deviator to yield a 99 percent spectral occupancy characteristic. The measurement procedure entailed the obtaining of a plot of the RF spectral power density as a function of frequency and the integration of the spectral density by means of a planimeter. The results of these measurements are given in Figures 69 through 75. All of the data presented, which carry the Performance Level I (1 Bps/Hz) and Performance Level II (2 Bps/Hz) designations implies the attainment of a 99 percent spectral occupancy characteristic.

An alternate spectral occupancy definition which has been proposed by the FCC in their Docket 19311 is based on the power vs. frequency characteristics of the transmitted signal rather than the percentage of energy within the assigned bandwidth. The requirement follows. The attenuation of the transmitted spectrum relative to the mean unmodulated power in a 4-kHz band shall not be less than that given by the following relationship:

$$A = 35 + .8\ (P - 50) + 10\ \log_{10} B$$

where

A = Attenuation (in decibels) below the mean output power level

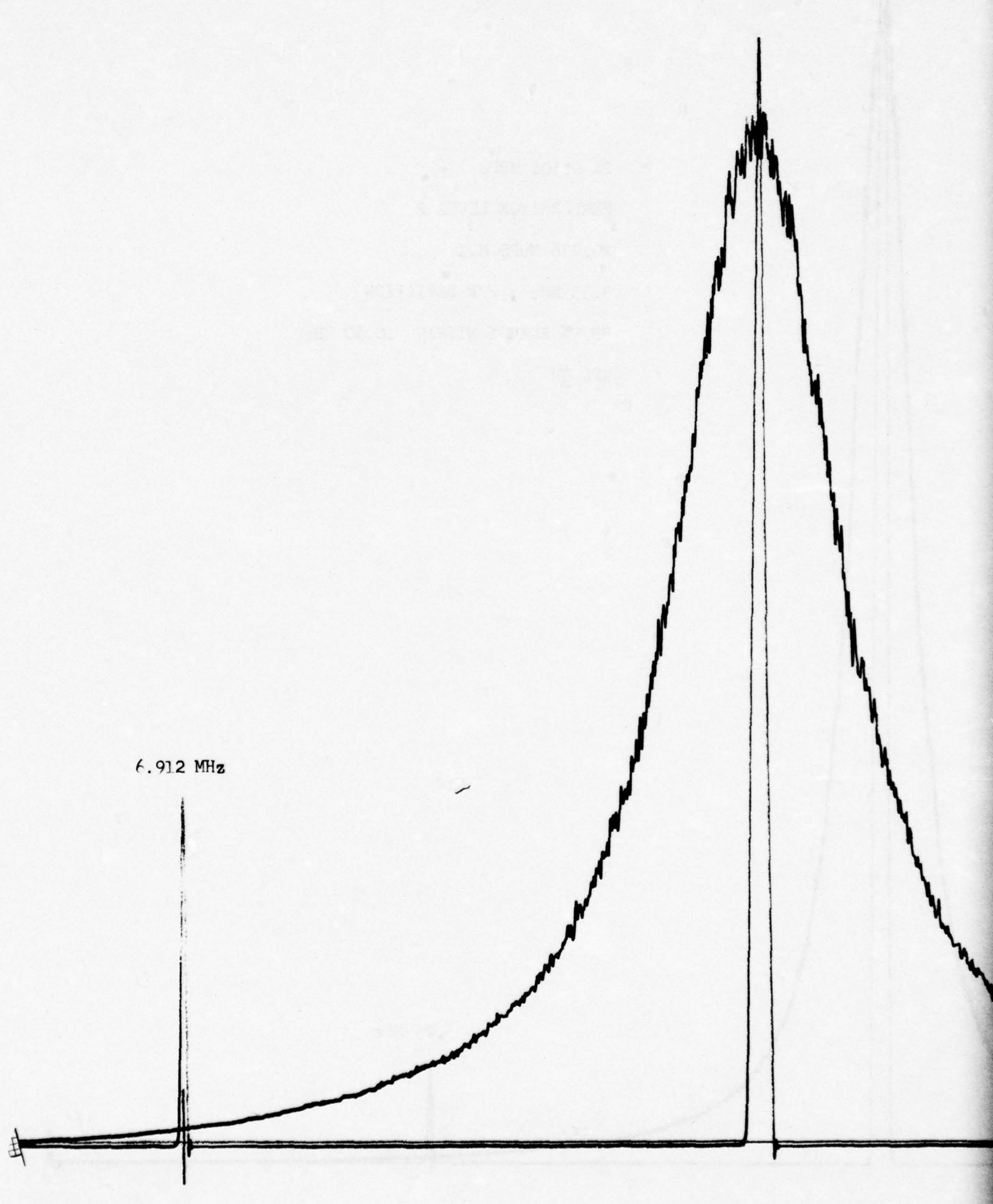
P = Percent removed from the carrier center frequency relative to authorized bandwidth

B = Authorized bandwidth in MHz

These attenuation values shall govern for frequencies removed from the center frequency by more than 50 percent. Attenuation in these areas shall not be less than 50 dB and attenuation greater than 80 dB is not required.

One advantage of the mask definition is that it may be easier to apply than the energy bandwidth criteria. However, the 80 dB attenuation requirement cannot be readily measured on most spectrum analyzers. Of greater significance is the possibility that the mask be unnecessarily severe. Most digital signals have "tails" which are substantially down from the carrier but taper off relatively slowly. Therefore, RF filters will be necessary for any modulation technique, which makes performance level changes (Table 13) and data rate changes difficult. Also, RF filters, especially narrowband ones, are lossy which decreases the

POWER Vs FREQUENCY



FREQUENCY

2

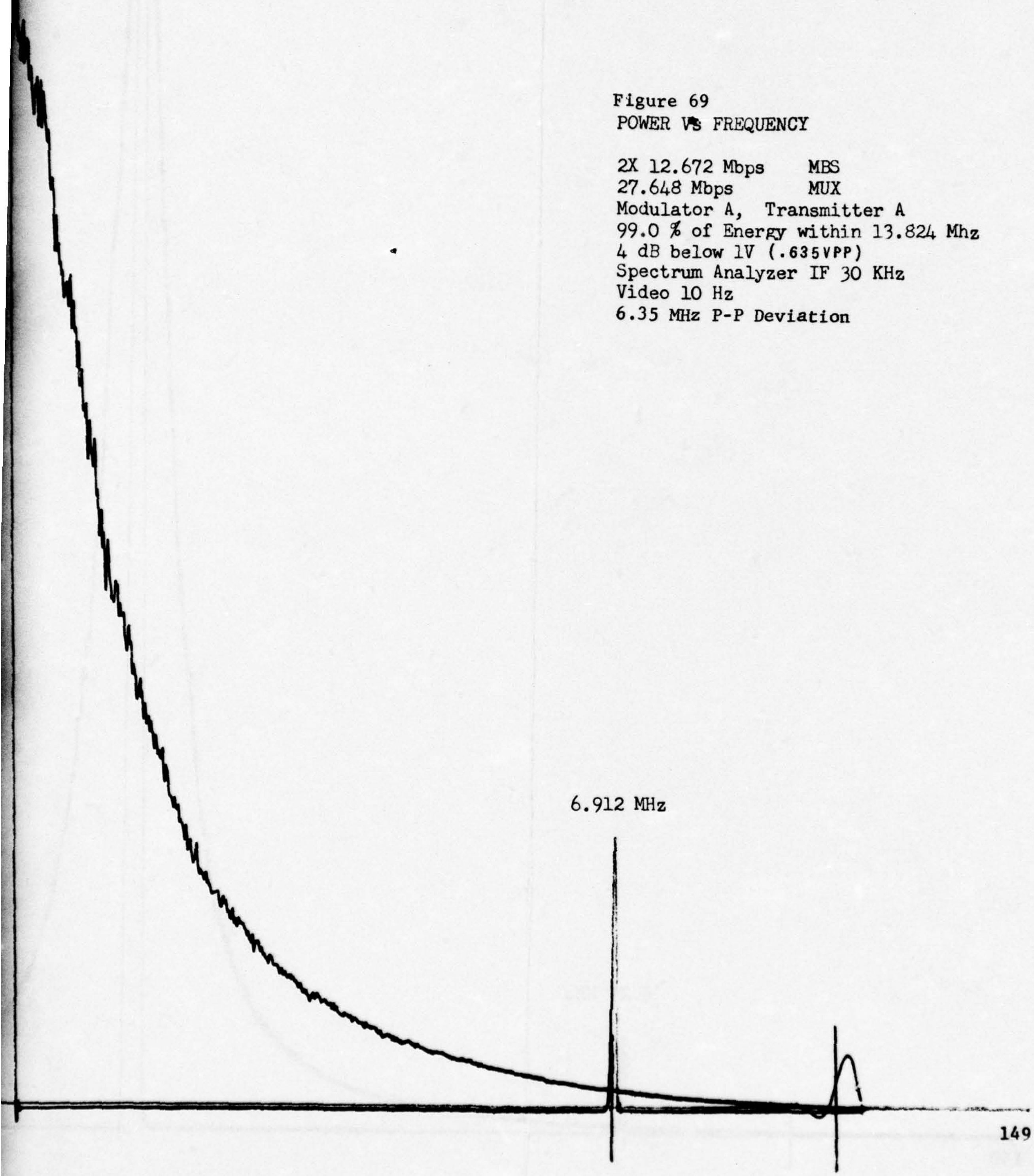
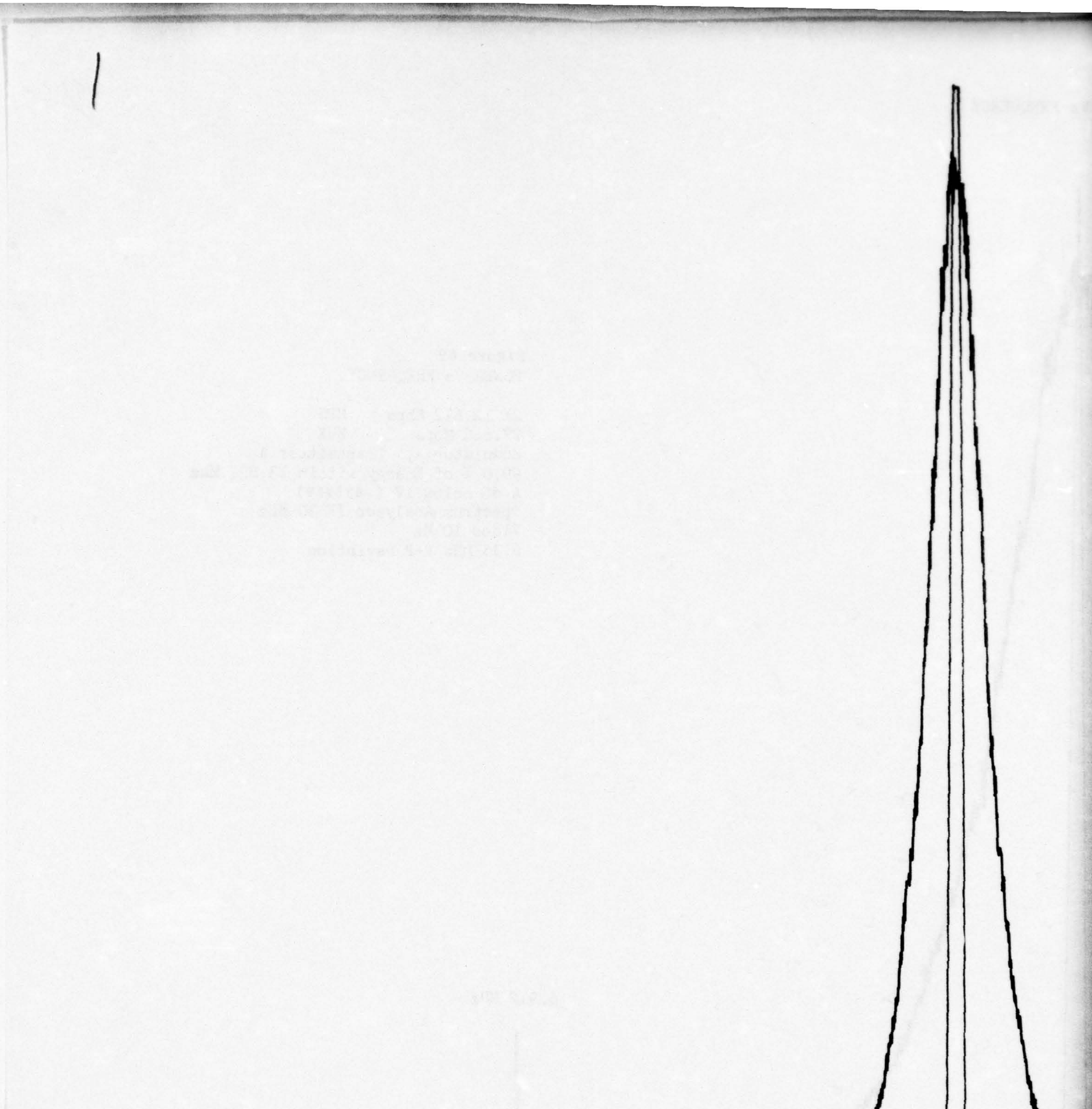


Figure 69
POWER VS FREQUENCY

2X 12.672 Mbps MBS
27.648 Mbps MUX
Modulator A, Transmitter A
99.0 % of Energy within 13.824 Mhz
4 dB below 1V (.635VPP)
Spectrum Analyzer IF 30 KHz
Video 10 Hz
6.35 MHz P-P Deviation


5.25 MHz
150

2

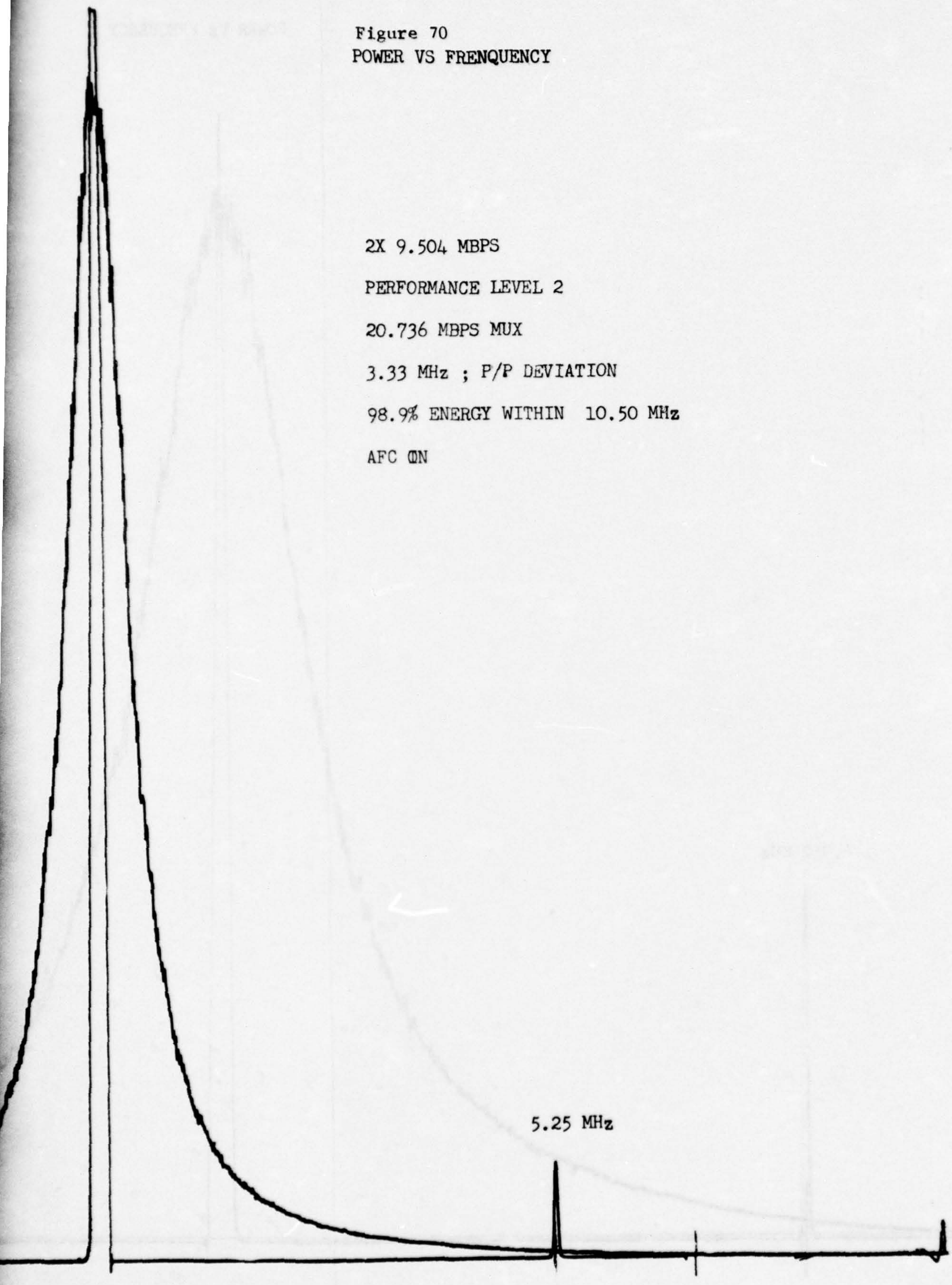
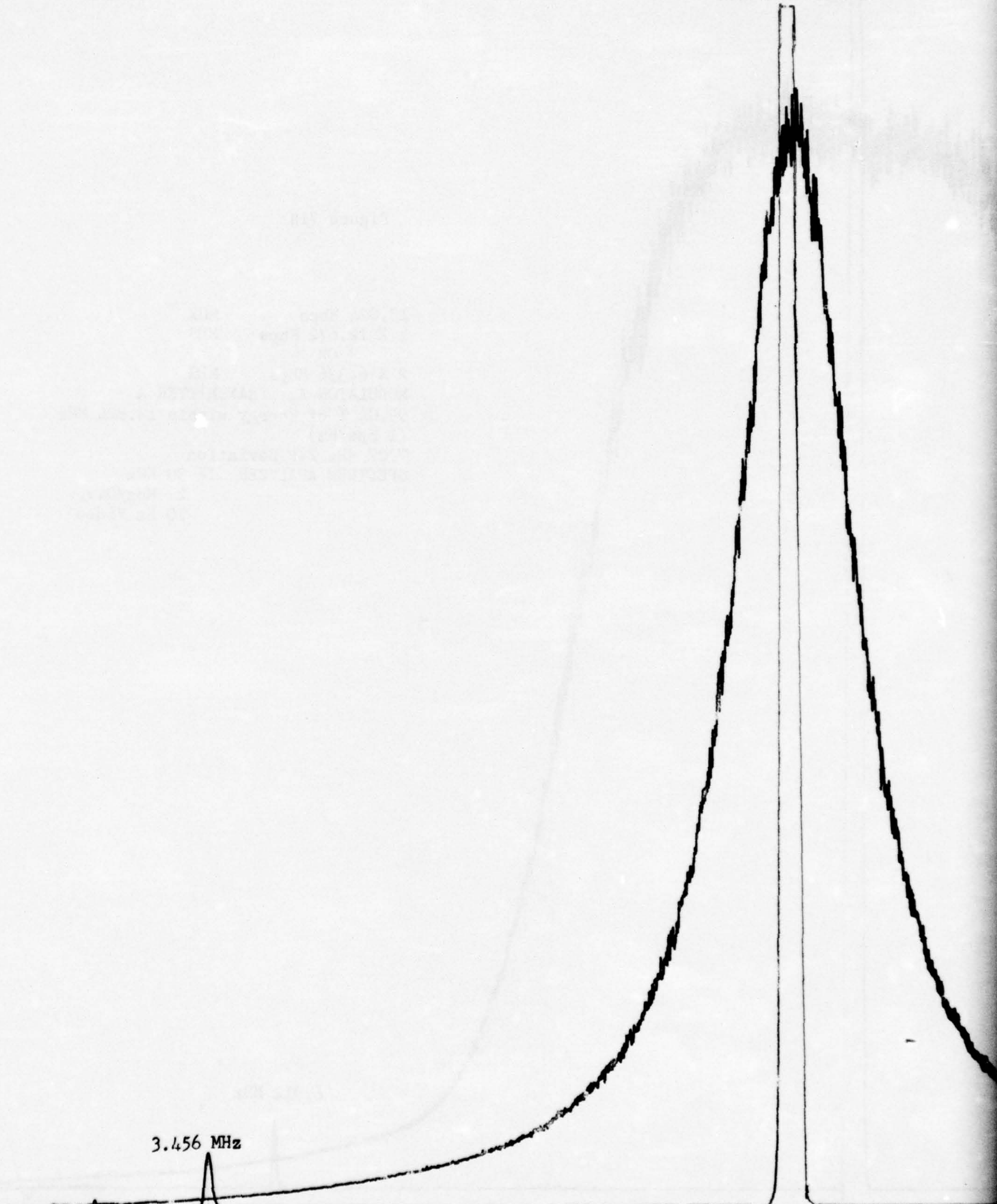


Figure 70
POWER VS FRENQUENCY


POWER Vs FREQUENCY
3.456 MHz

FREQUENCY

2

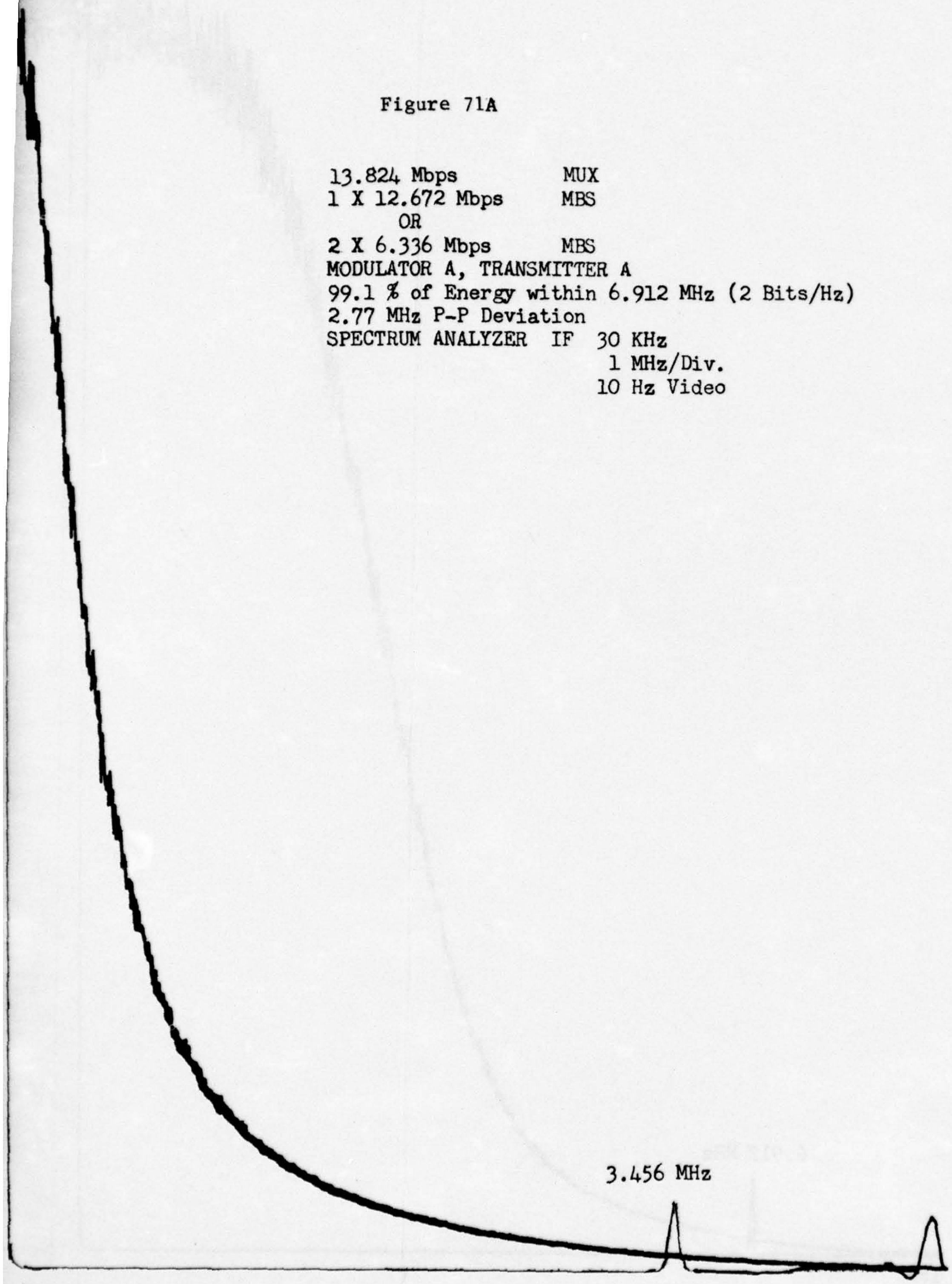
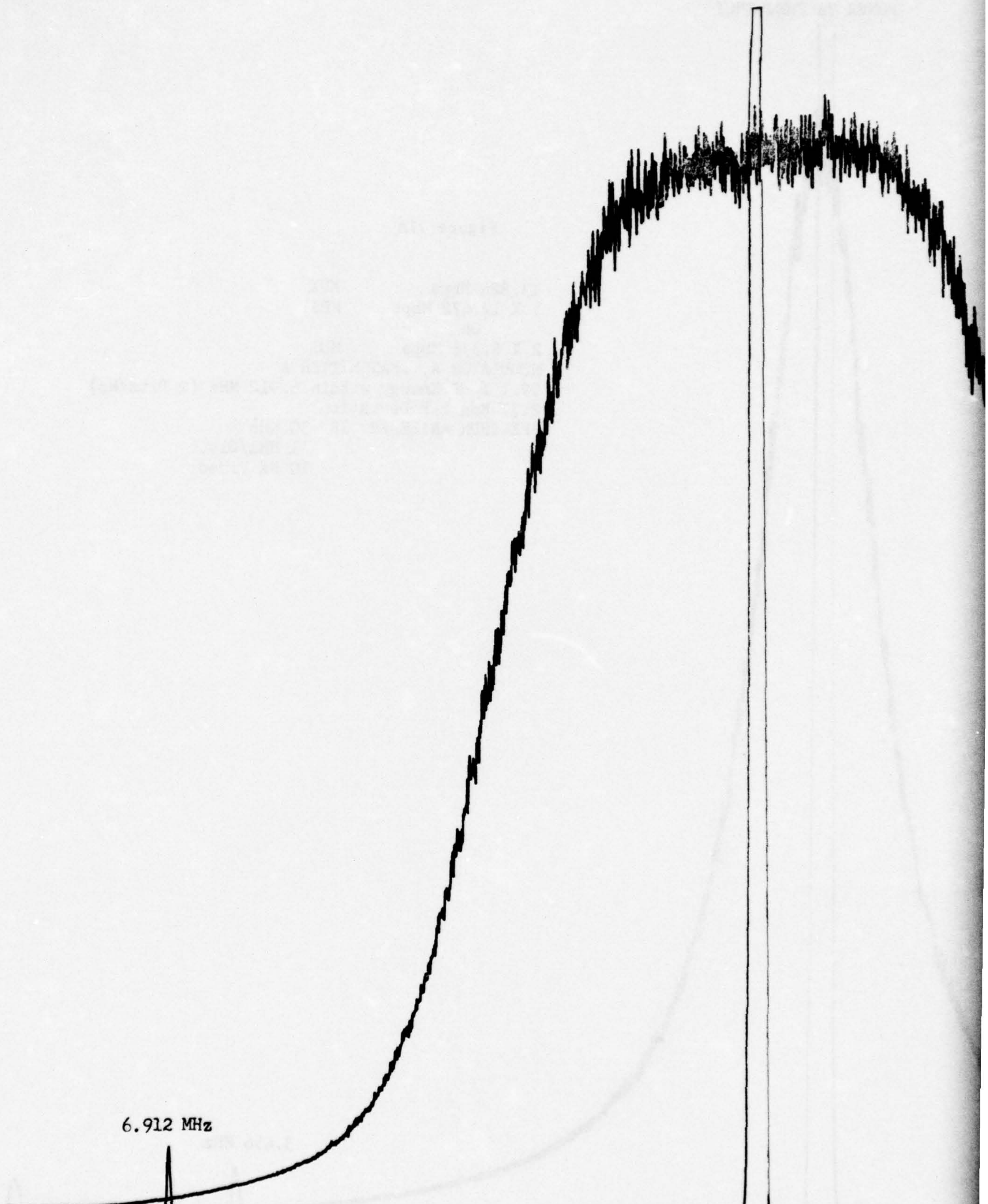


Figure 71A

13.824 Mbps MUX
1 X 12.672 Mbps MBS
OR
2 X 6.336 Mbps MBS
MODULATOR A, TRANSMITTER A
99.1 % of Energy within 6.912 MHz (2 Bits/Hz)
2.77 MHz P-P Deviation
SPECTRUM ANALYZER IF 30 KHz
1 MHz/Div.
10 Hz Video

POWER Vs FREQUENCY

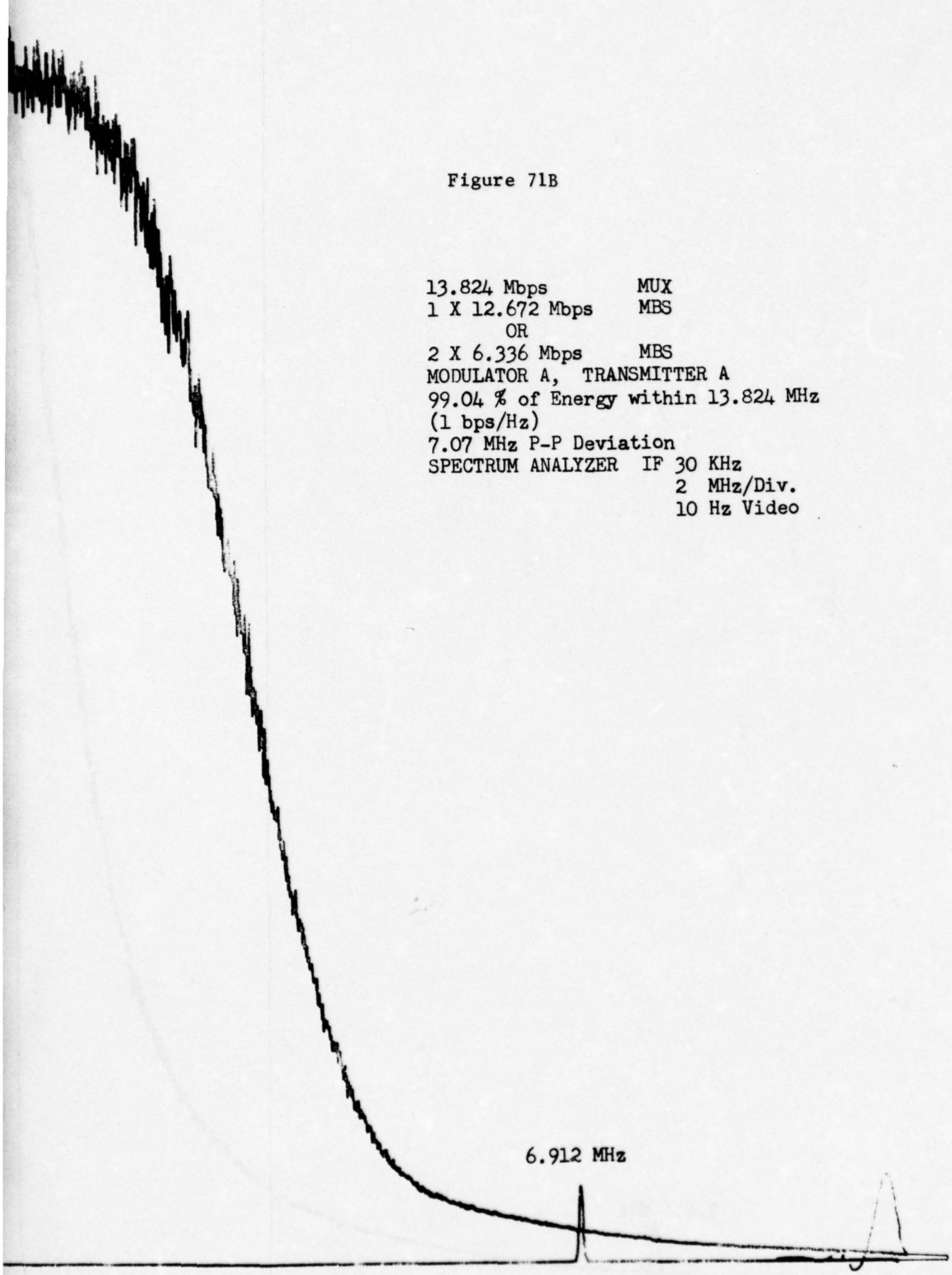


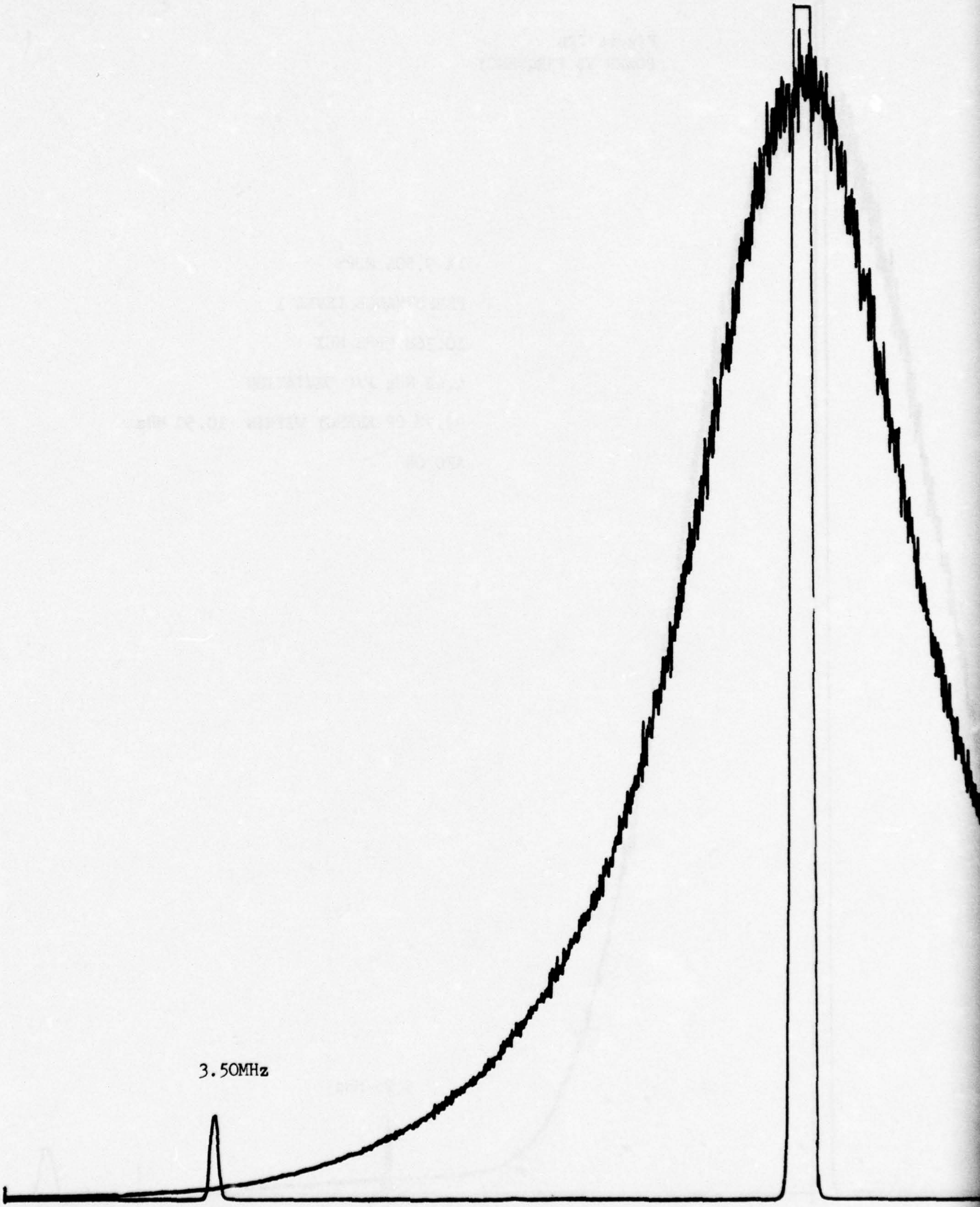
NCY

2

Figure 71B

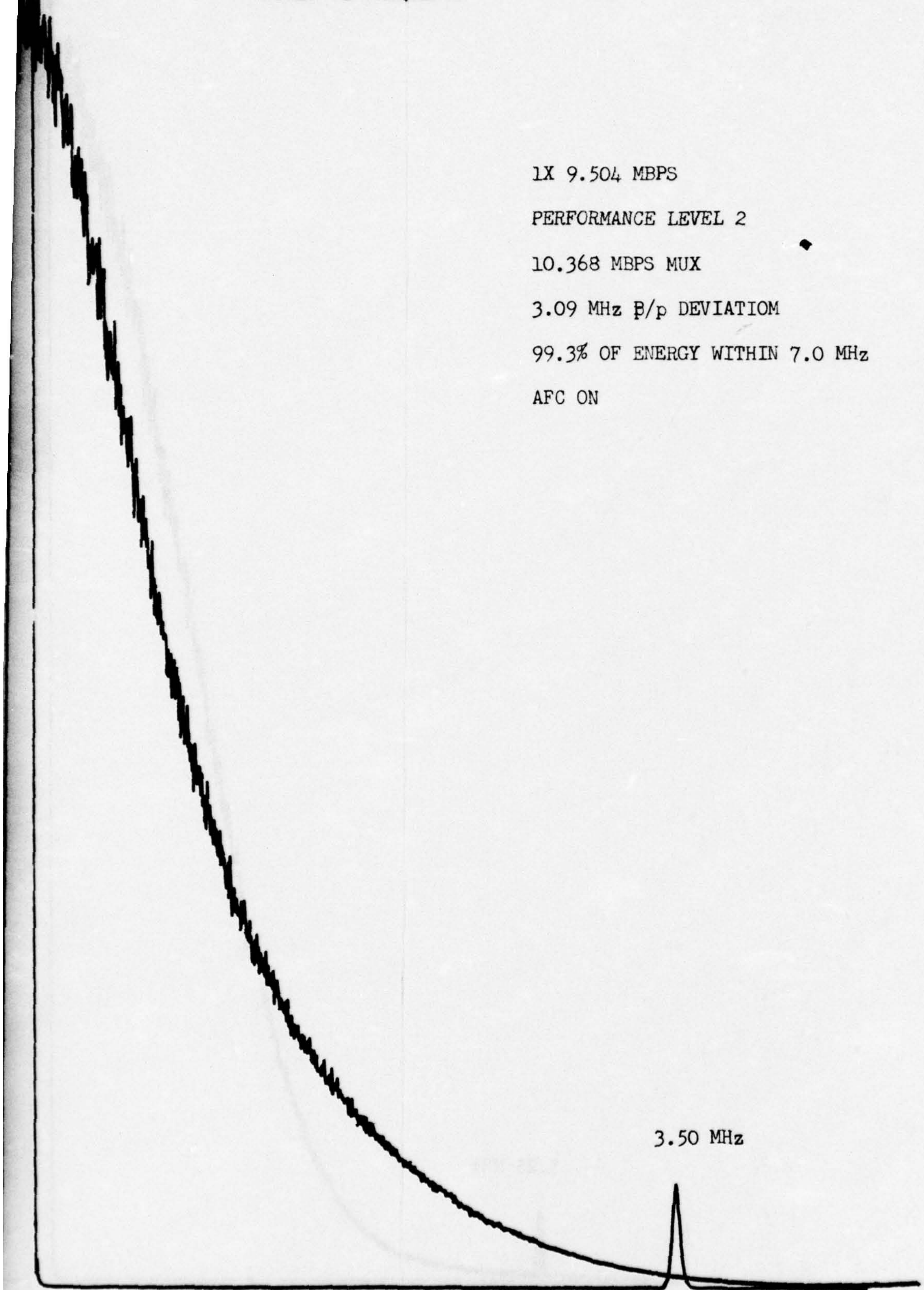
13.824 Mbps MUX
1 X 12.672 Mbps MBS
OR
2 X 6.336 Mbps MBS
MODULATOR A, TRANSMITTER A
99.04 % of Energy within 13.824 MHz
(1 bps/Hz)
7.07 MHz P-P Deviation
SPECTRUM ANALYZER IF 30 KHz
2 MHz/Div.
10 Hz Video




3.50MHz

2

Figure 72A
POWER VS FREQUENCY



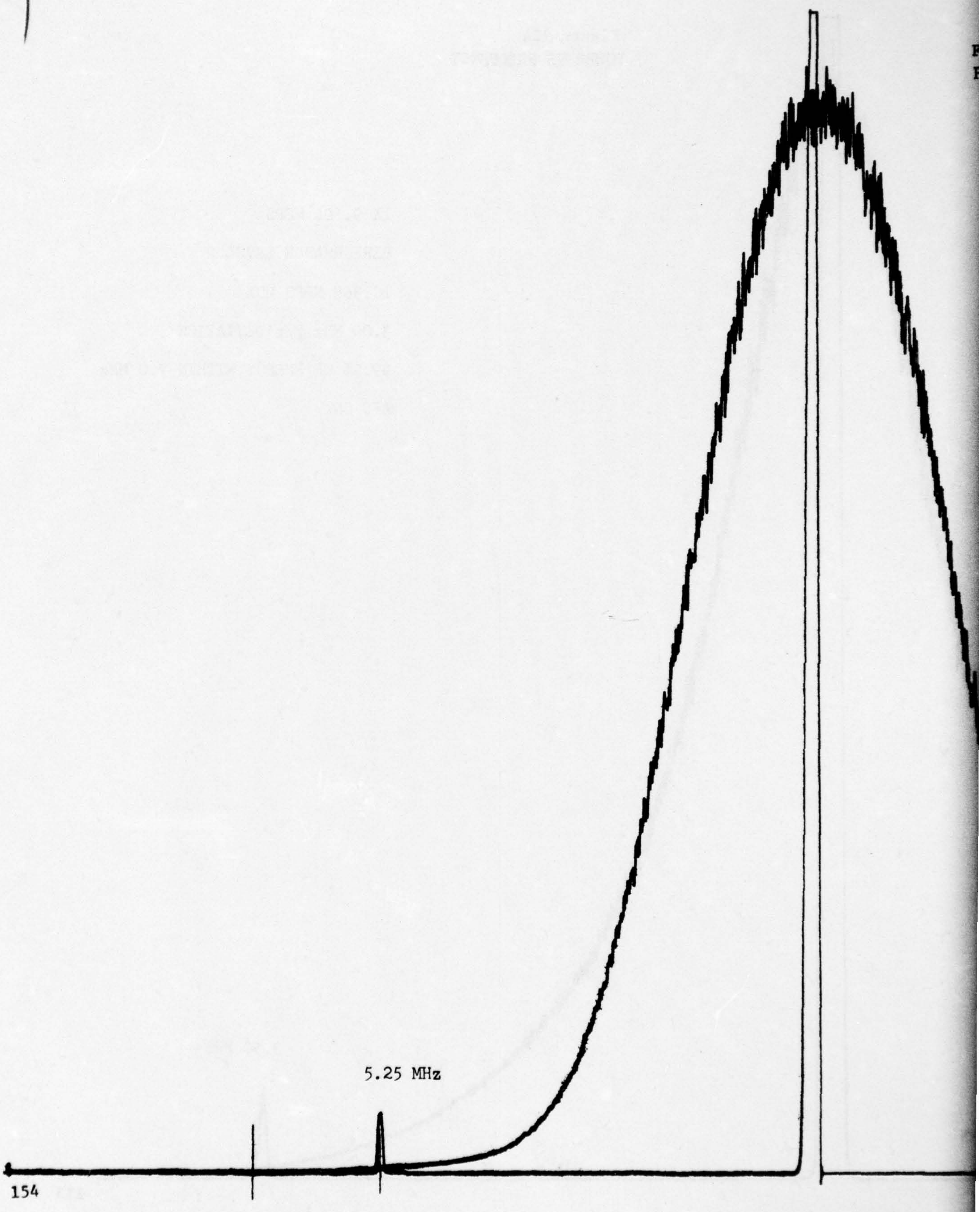
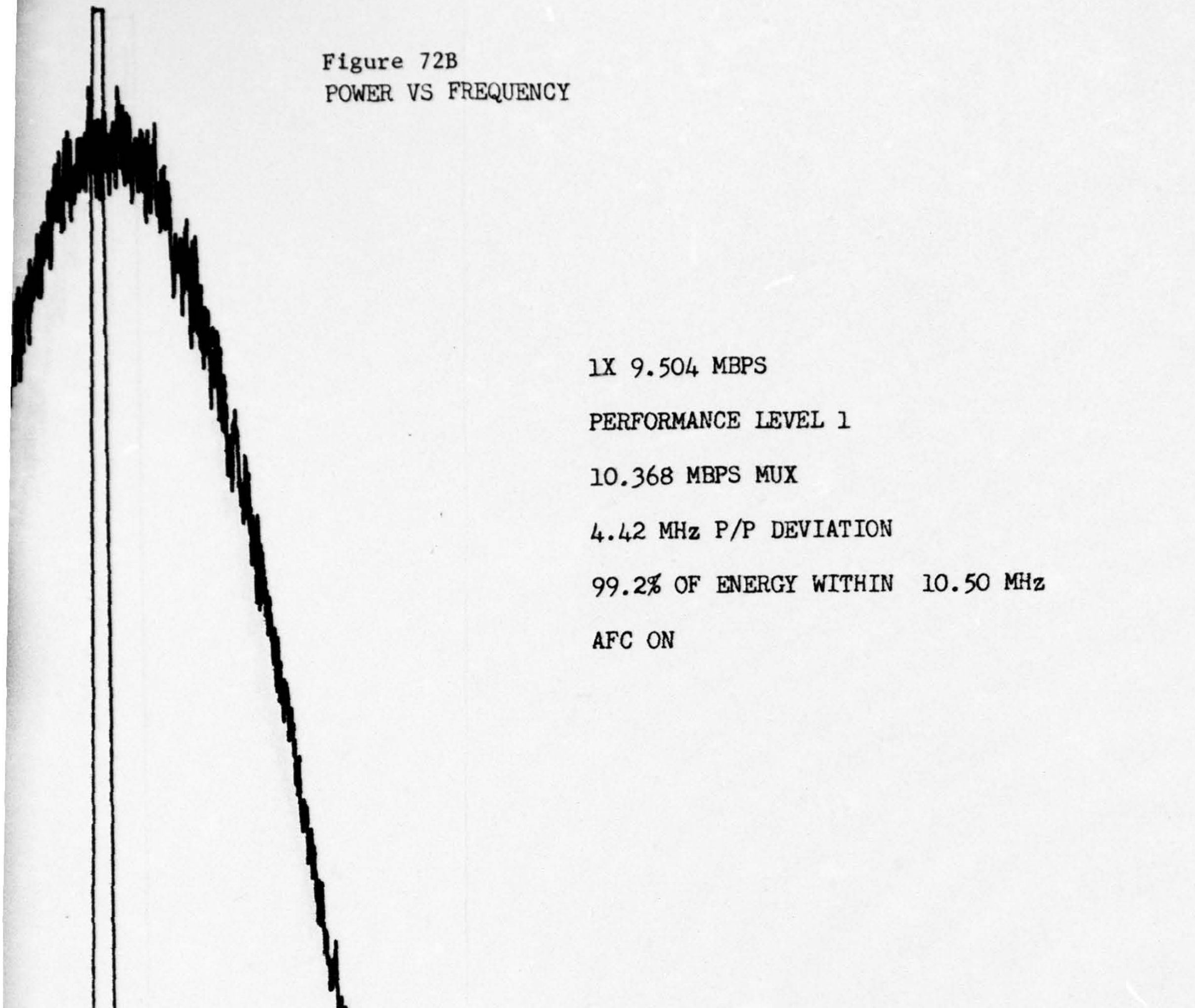
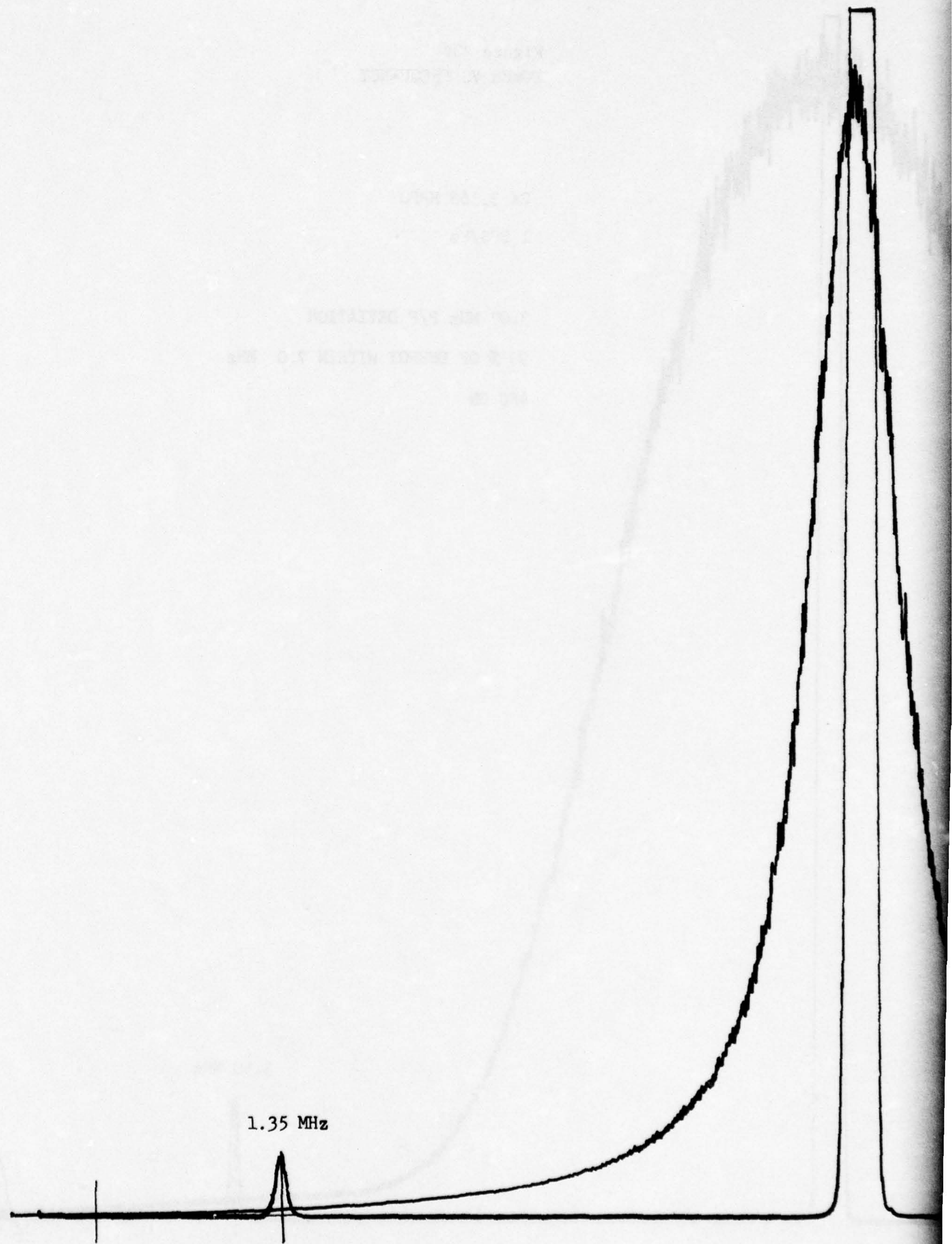

5.25 MHz
154

Figure 72B
POWER VS FREQUENCY



1



1 2

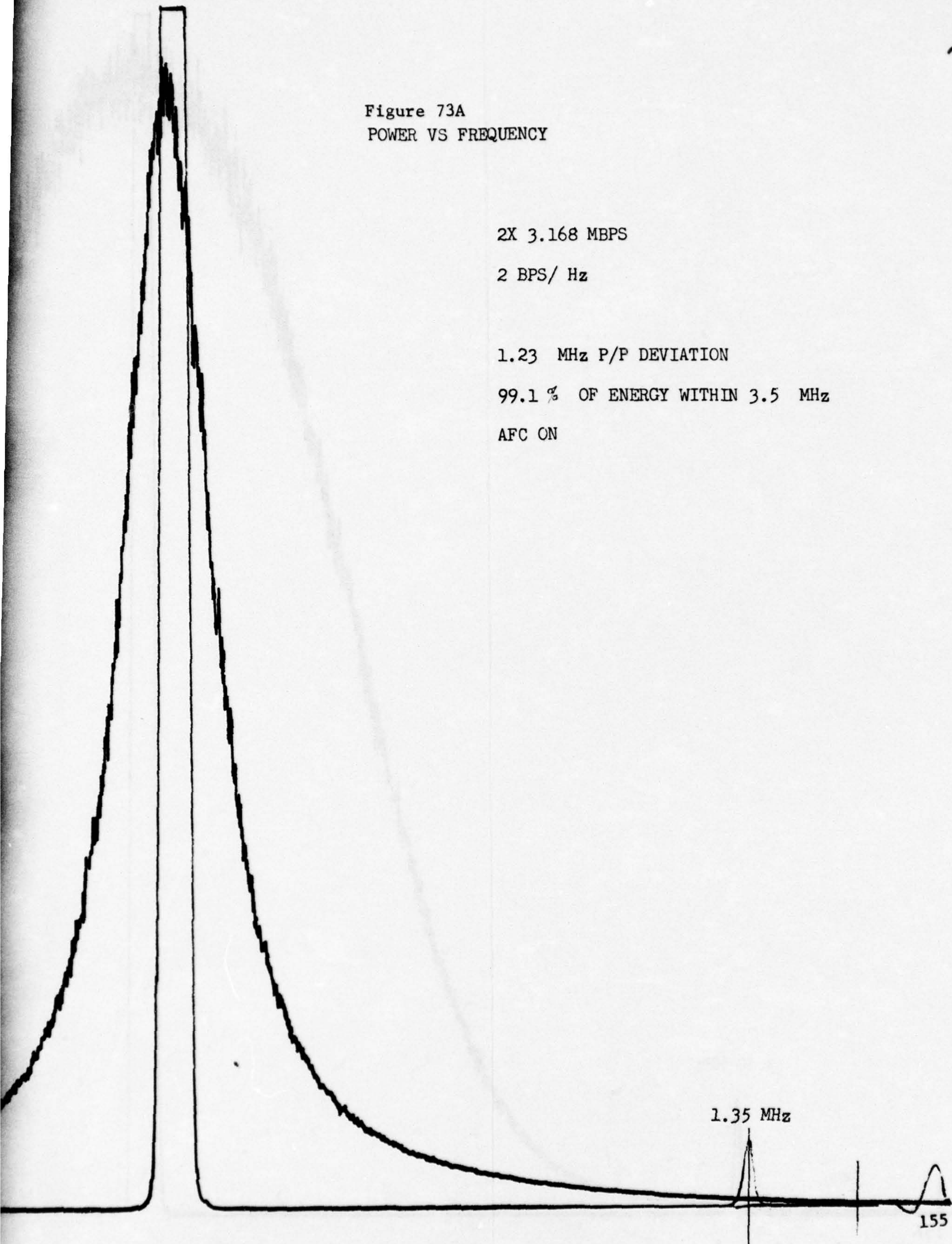
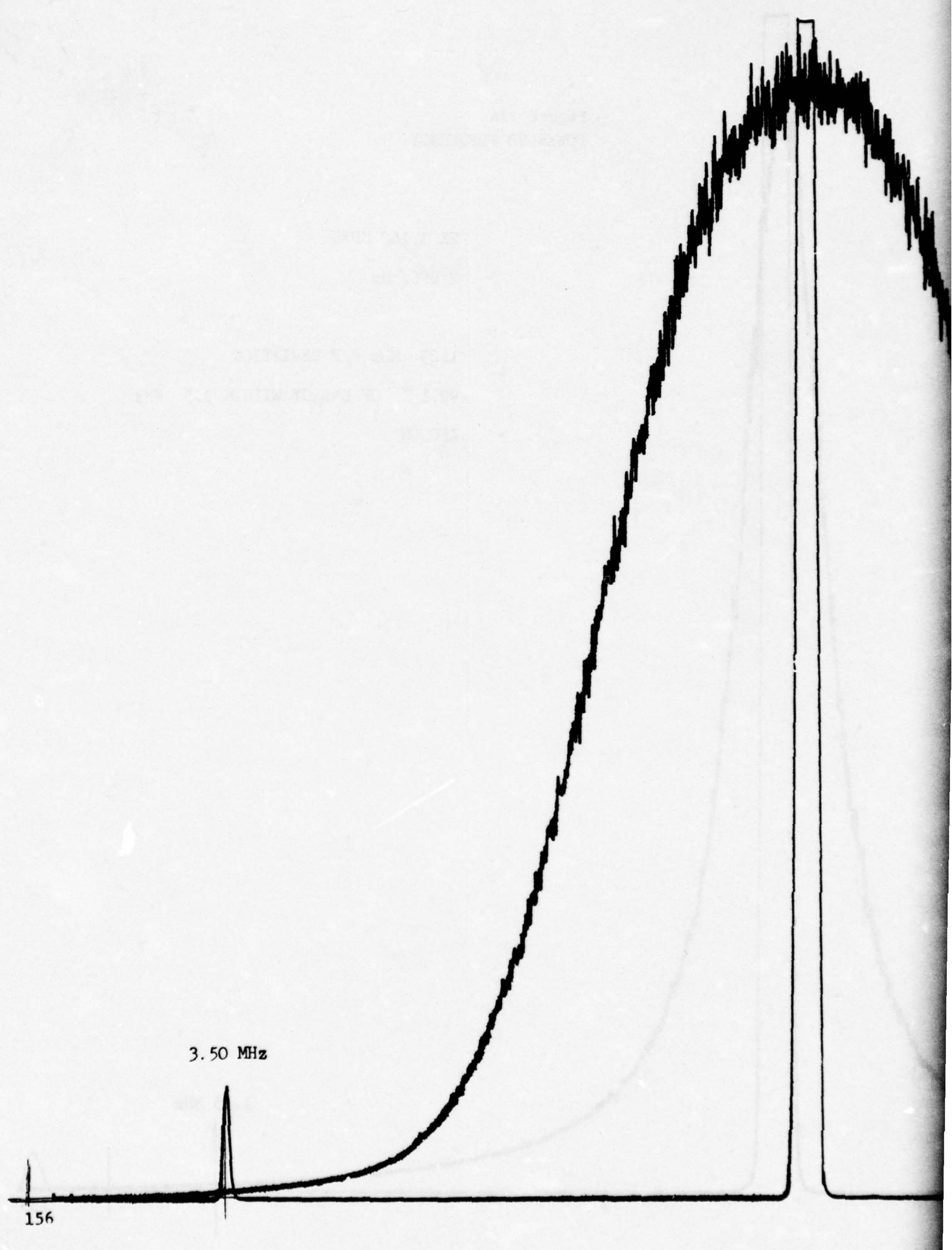


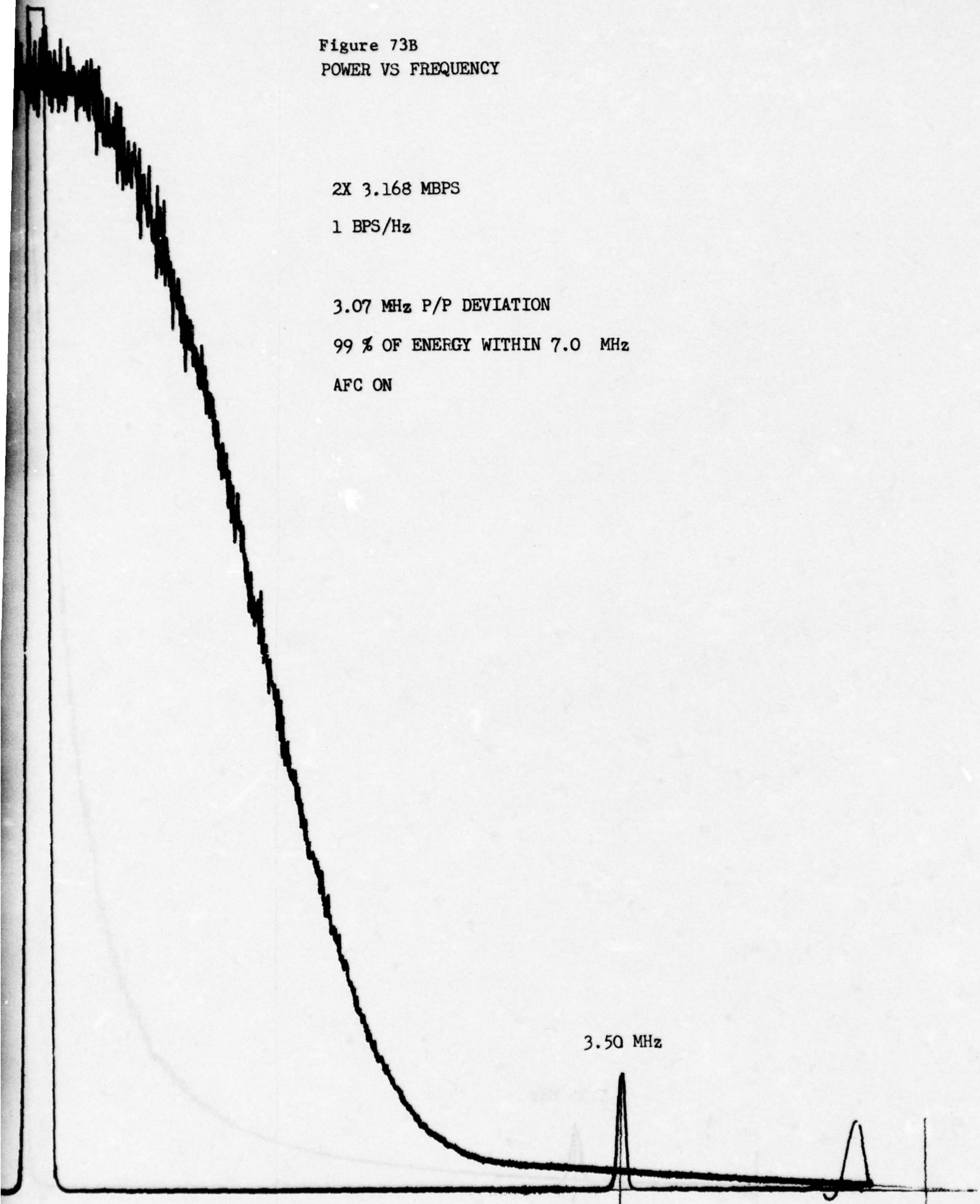
Figure 73A
POWER VS FREQUENCY

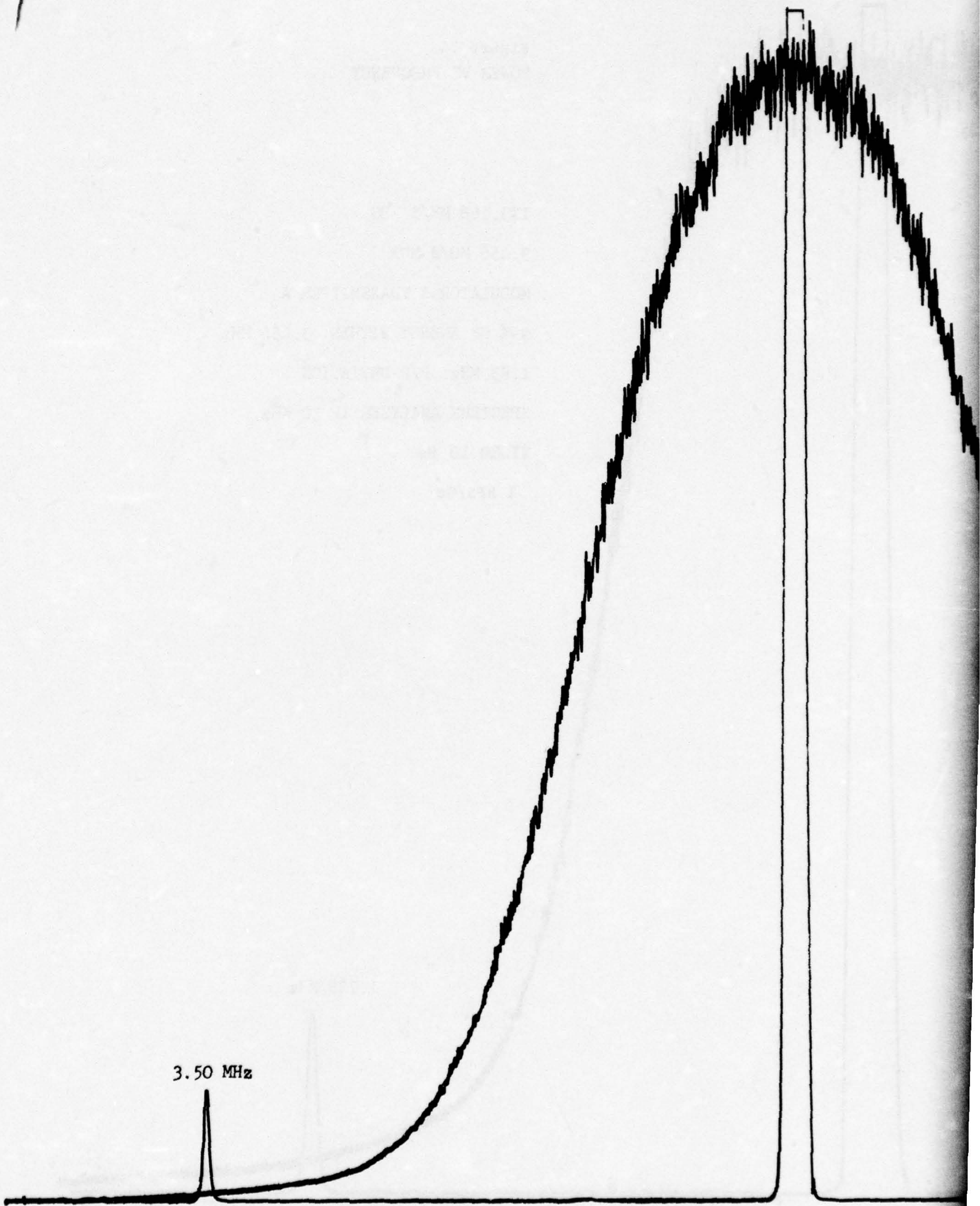


3.50 MHz
156

2

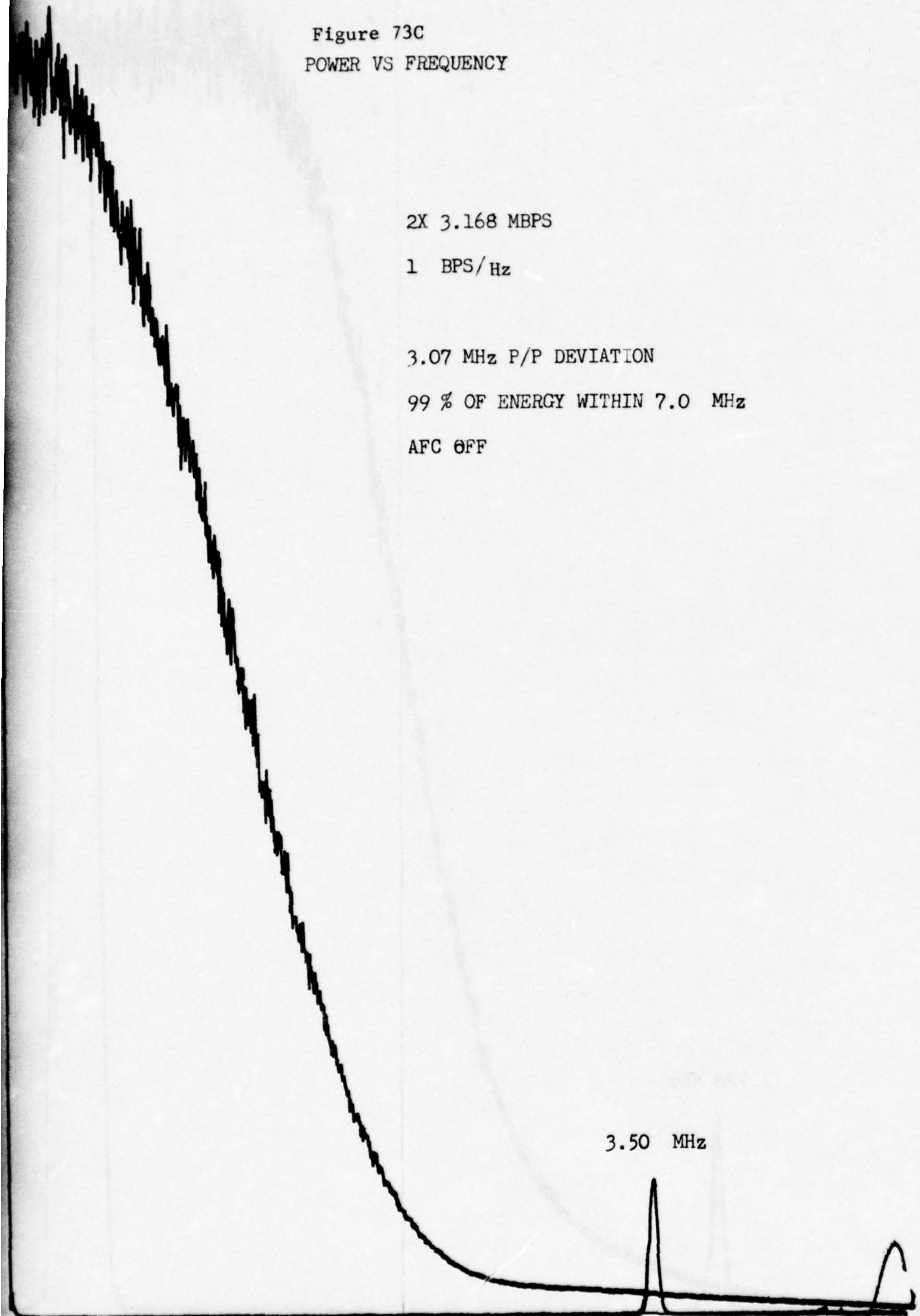
Figure 73B
POWER VS FREQUENCY

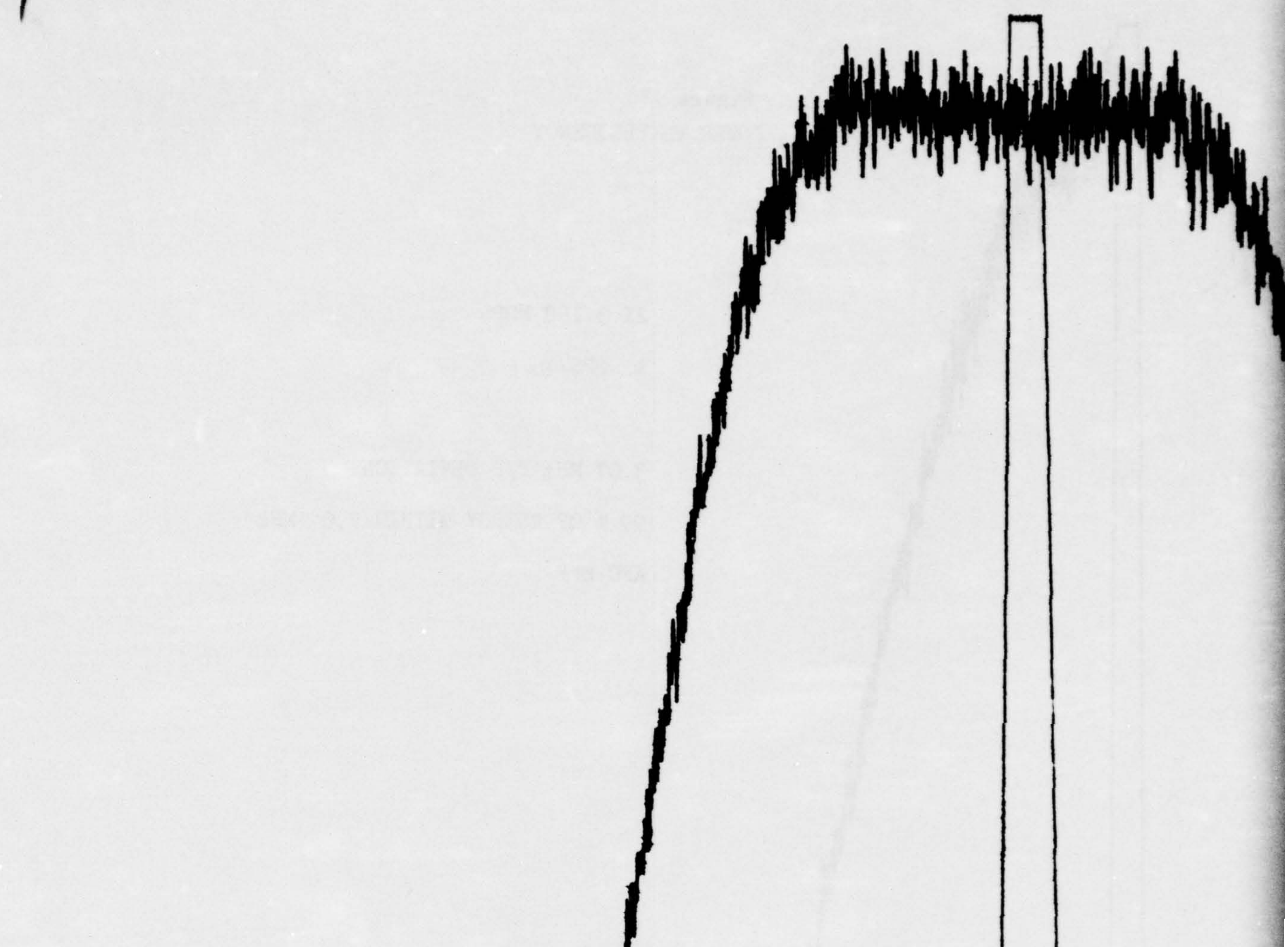



3.50 MHz

2

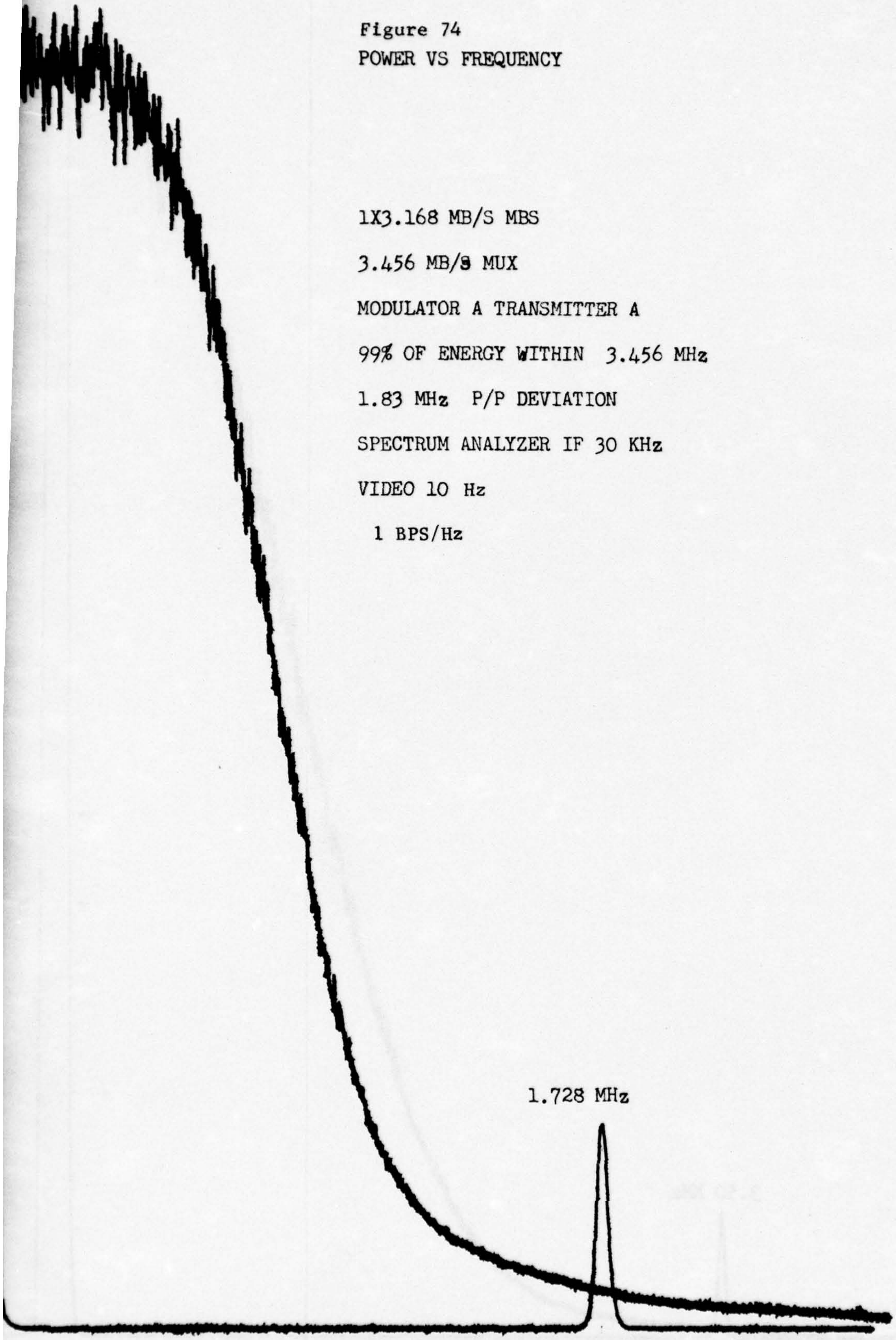
Figure 73C
POWER VS FREQUENCY

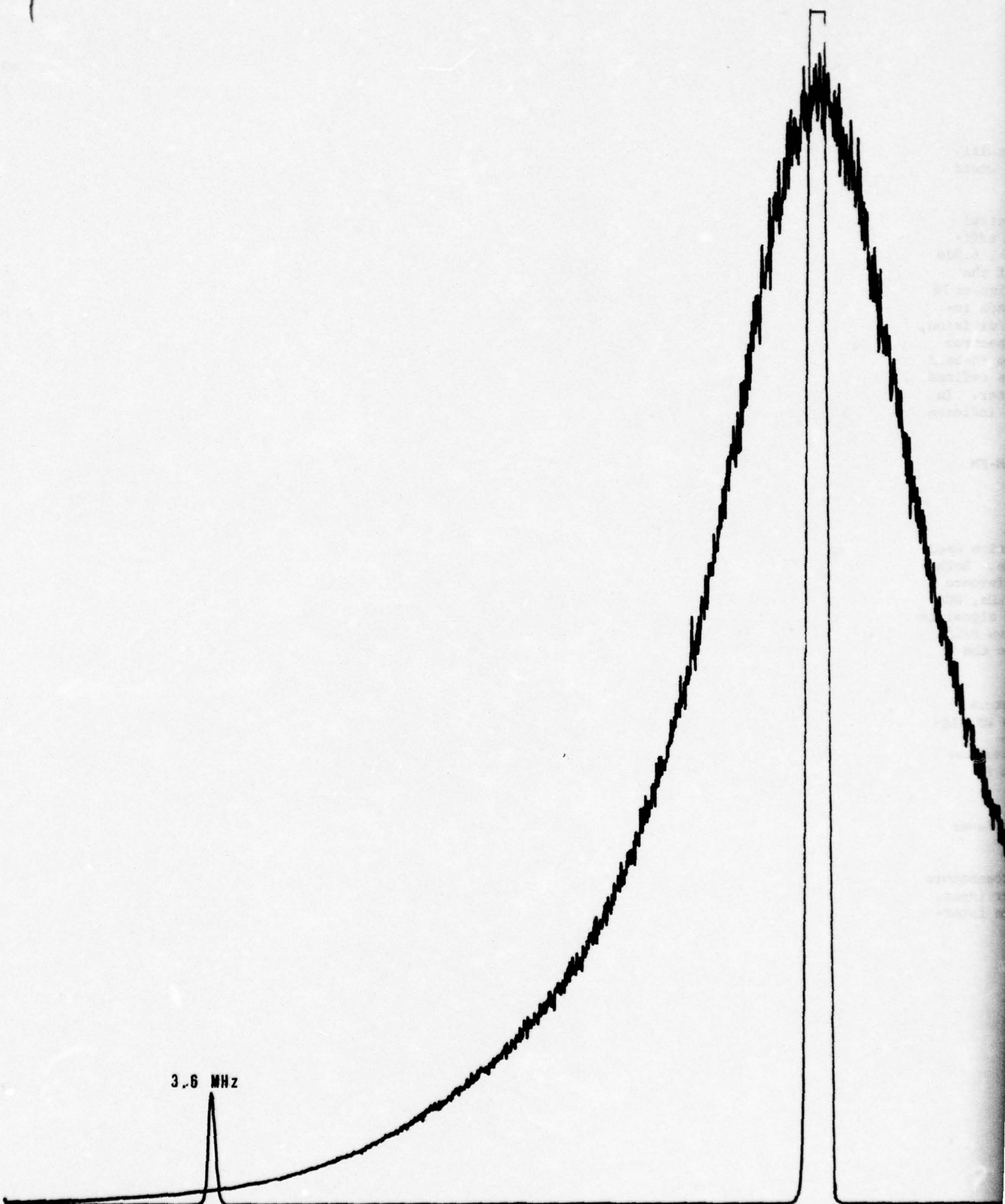



1.728 MHz

2

Figure 74
POWER VS FREQUENCY

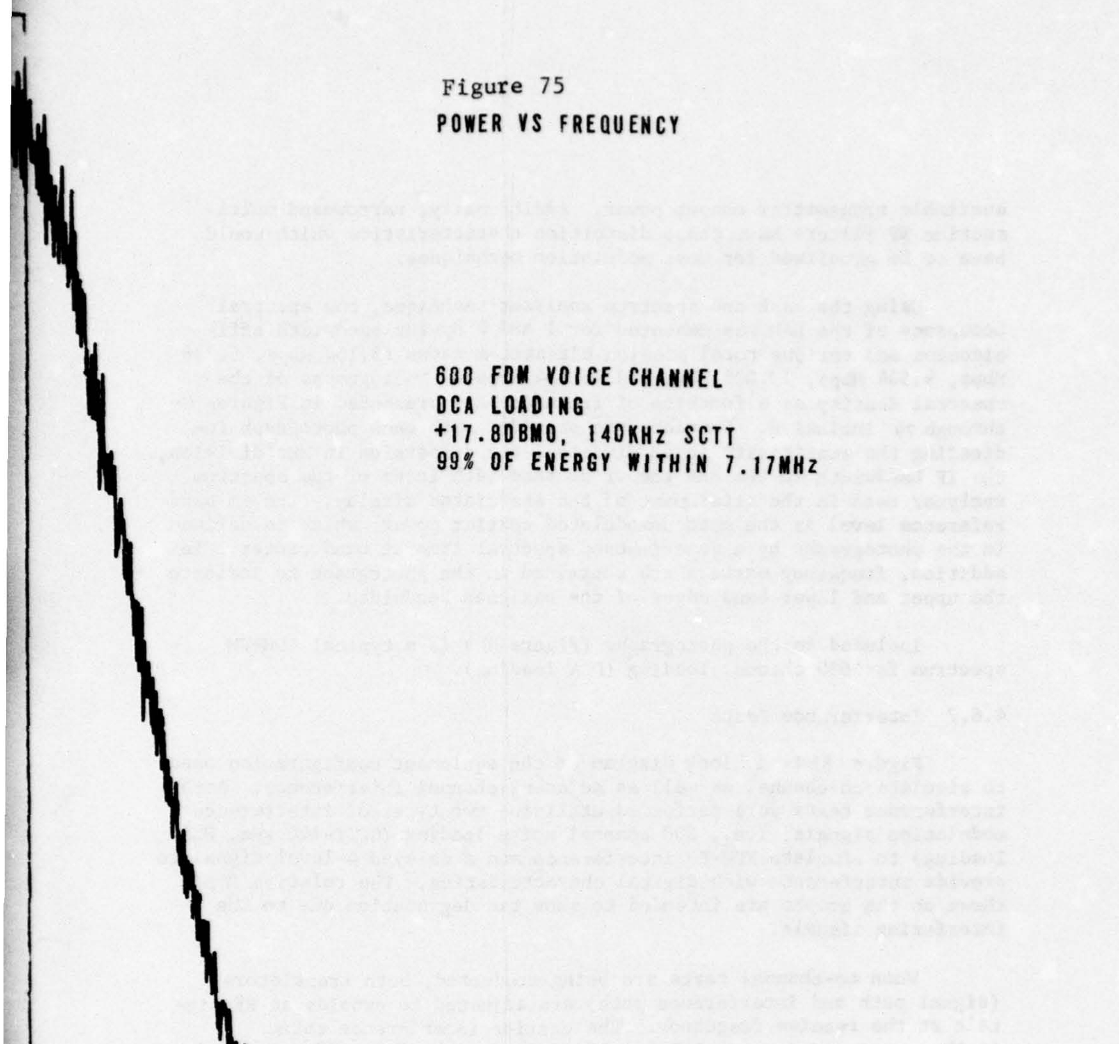



3.6 MHz

2

Figure 75

POWER VS FREQUENCY



available transmitter output power. Additionally, narrowband multisection RF filters have phase distortion characteristics which would have to be equalized for most modulation techniques.

Using the mask and spectrum analyzer technique, the spectral occupancy of the DAU was measured for 1 and 2 Bps/Hz bandwidth efficiencies and various total mission bit stream rates (3.168 Mbps, 6.336 Mbps, 9.504 Mbps, 19.008 Mbps and 25.354 Mbps). Photographs of the spectral density as a function of frequency are presented in Figures 76 through 79 inclusive. Captions are provided with each photograph indicating the sensitivity in dB/division, the dispersion in MHz/division, the IF bandwidth in kHz and the video bandwidth in Hz of the spectrum analyzer used in the attainment of the associated display. The in-band reference level is the mean unmodulated carrier power, which is defined in the photographs by a superimposed spectral line at band center. In addition, frequency markers are contained in the photograph to indicate the upper and lower band edges of the assigned bandwidth.

Included in the photographs (Figure 80) is a typical FDM-FM spectrum for 600 channel loading (DCA loading).

4.6.7 Interference Tests

Figure 81 is a block diagram of the equipment configuration used to simulate co-channel as well as adjacent-channel interference. Both interference tests were performed utilizing two types of interference modulation signals; i.e., 600 channel noise loading (SCTT-140 kHz, DCA loading) to simulate FDM-FM interference and a delayed 4-level signal to provide interference with digital characteristics. The relative RSL's shown on the graphs are intended to show the degradation due to the interfering signals.

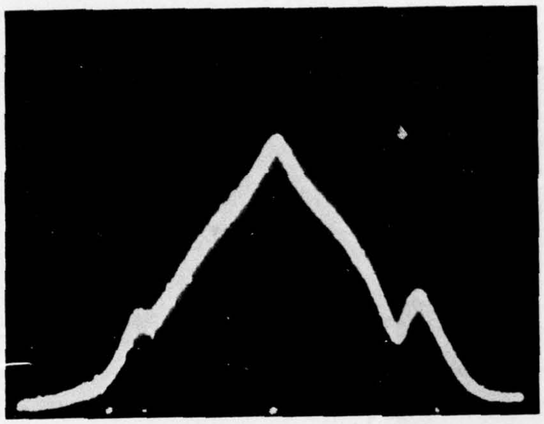
When co-channel tests are being conducted, both translators (signal path and interference path) are adjusted to provide an RF signale at the receive frequency. The carrier interference ratio is the parameter for the BER vs. RSL data for the four MBS rates and performance level combinations presented in Figures 82 through 85 inclusive.

In general, a carrier to interference ratio of 23 dB produces a relatively small degradation in BER vs. RSL performance.

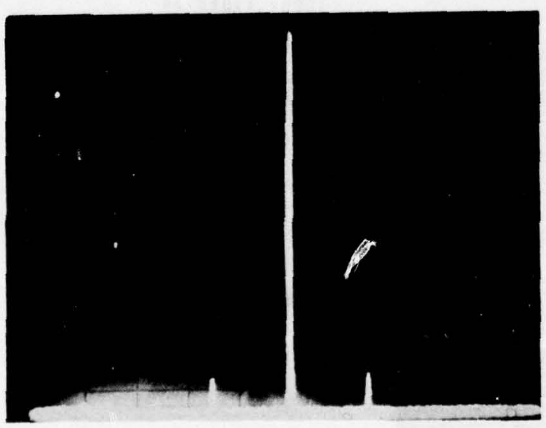
To conduct adjacent-channel interference tests, both attenuators are set to produce equal level RF signals at the radio receiver input. The frequency displacement (controlled by the translator in the interference path) is now the parameter for the BER vs. RSL data

Figure 76

TRANSMITTED SPECTRUM DUAL 12.672MBPS MBS RATE

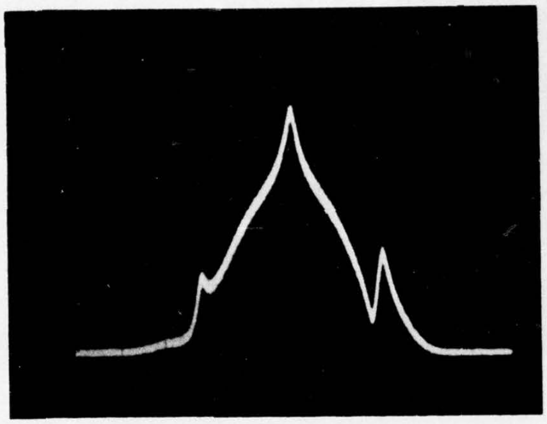


HORIZ. 5MHz/DIV
VERT. 10dB/DIV.
10KHz IF BW
10HRz VIDEO BW



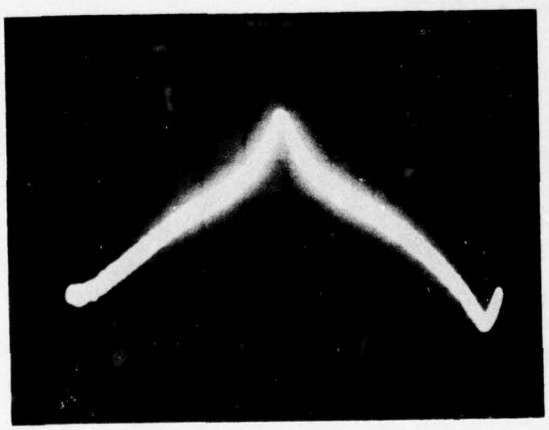
SAME AS ABOVE
EXCEPT
UNMODULATED CARRIER

Figure 77
TRANSMITTED SPECTRUM DUAL 9.504MBPS MBS RATE



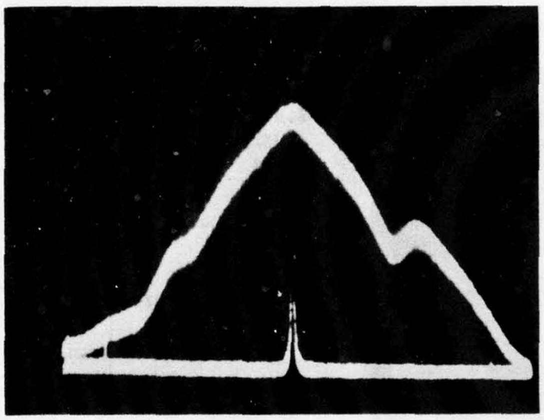
5MHz/DIV

3.33MHz P-P DEVIATION
PERFORMANCE LEVEL II
10DB/DIV
10KHz IF BW
100Hz VIDEO BW
TOP OF SIGNAL 18
DB BELOW UNMODULATED
CARRIER
-60DB (-64DB IN 4KHz)
@ F_C ±10.5MHz



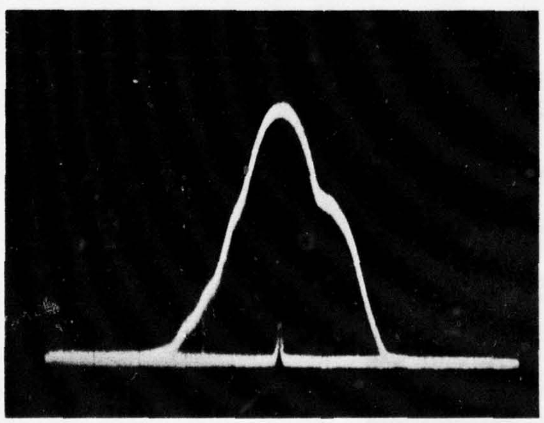
2MHz/DIV.

Figure 78
TRANSMITTED SPECTRUM SINGLE 9.504MBPS MBS RATE



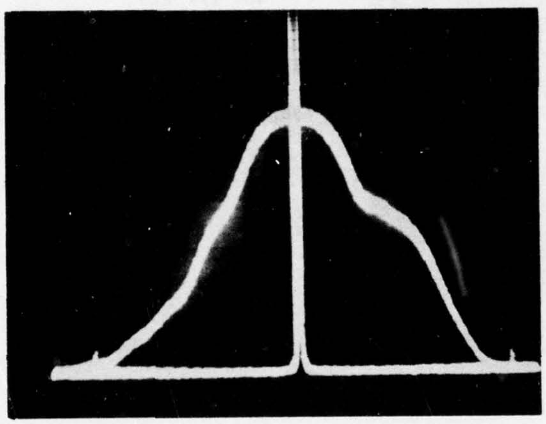
PERFORMANCE LEVEL II
3.09MHz P/P DEV.
2MHz/DIV
100Hz VIDEO BW
3KHz IF BW

55DB (53.8DB IN 4KHz)
@ F_C +7MHz



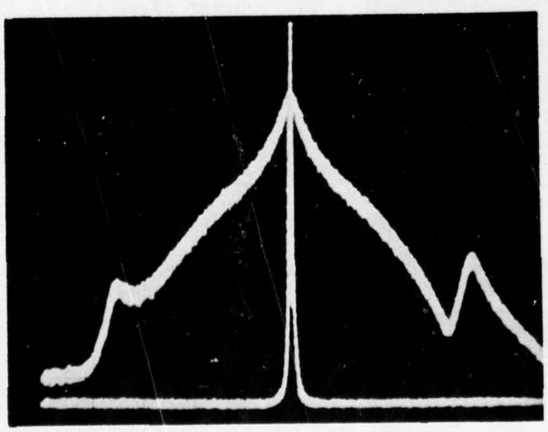
PERFORMANCE LEVEL I
4.42MHz P/P DEV.
5MHz/DIV
100Hz VIDEO BW
10Hz IF BW
>70DB @ F_C +10.7MHz

Figure 79
TRANSMITTED SPECTRUM DUAL 3.168MBPS MBS RATE



3.07MHz P/P
1BPS/Hz
10KHz IF BW

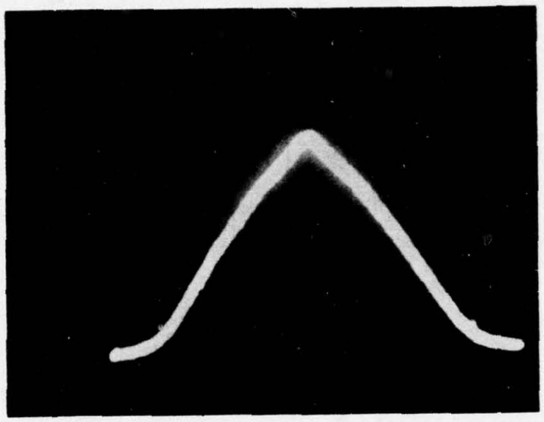
-44DB @ 3.5MHz
-70DB @ 7 MHz



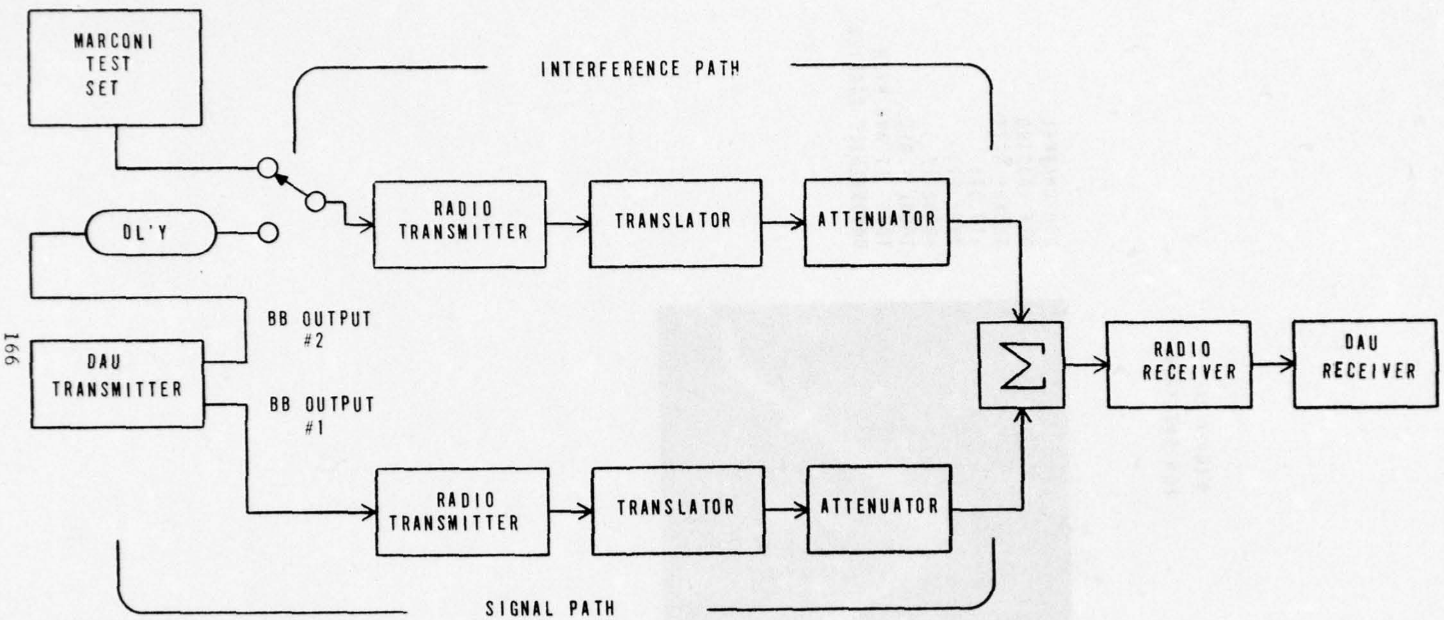
1.23MHz P/P
2BPS/Hz
-46DB @ +7MHz
1MHz/DIV.
>75DB @ ±14MHz

Figure 80

FDM SPECTRUM



600 CHANNEL
DCA LOADING
140KHz SCTT
+17.8DB
2MHz/DIV.
10KHz=IF
100Hz VIDEO
TOP: AT 0DB WITH
UNMODULATED CARRIER.



NOTES: 1. DL'Y IS EQUAL TO 1 BAUD.
2. MARCONI SET FOR 600 CH LOADING (SCTT-140kHz, DCA LOADING)

Figure 81
CO-CHANNEL AND ADJACENT - CHANNEL TEST CONFIGURATION BLOCK DIAGRAM

Figure 82

2X12.672MBPS BER VS CO-CHANNEL INTERFERENCE

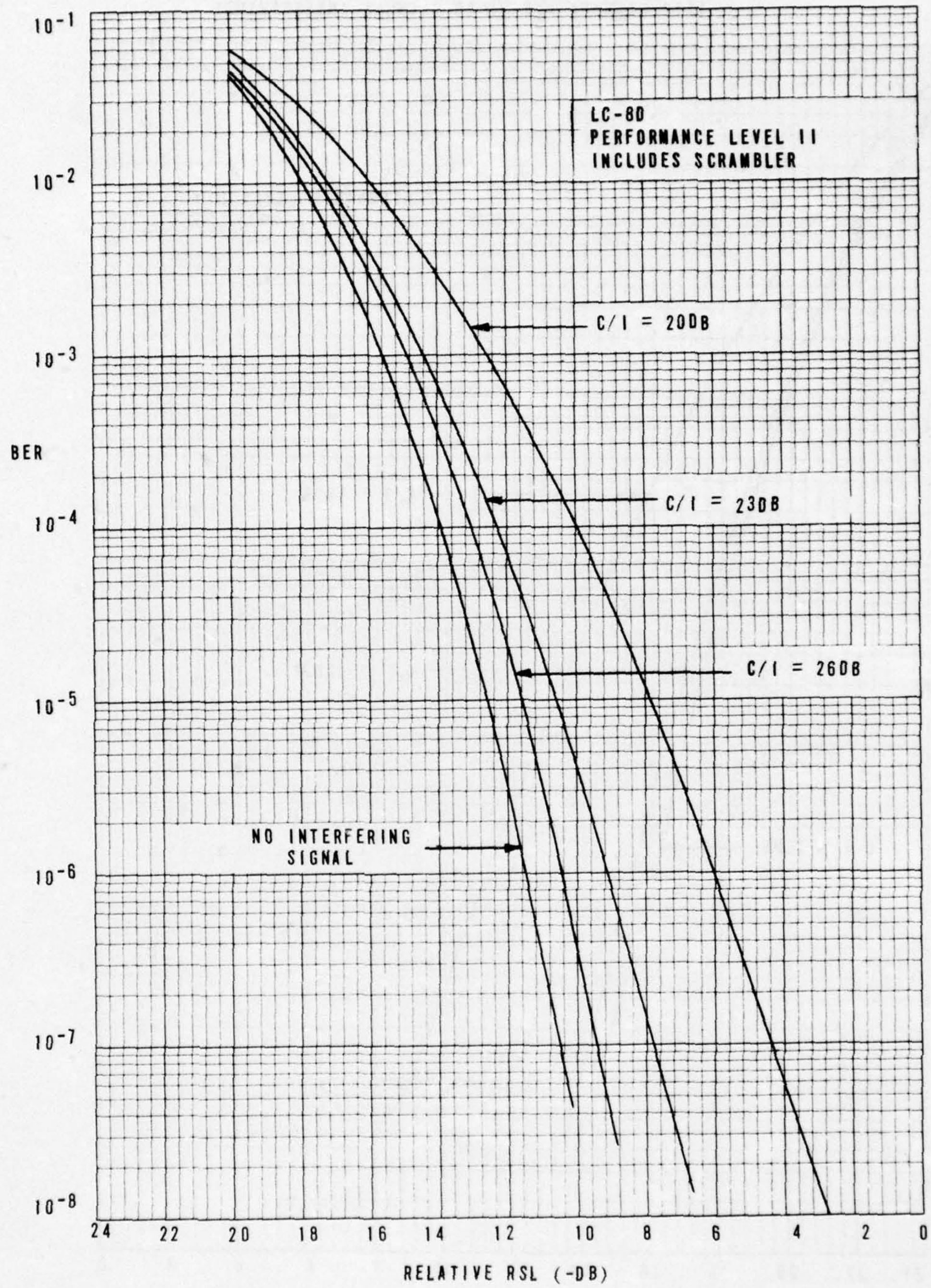


Figure 83

1X12.672MBPS BER VS CO-CHANNEL INTERFERENCE

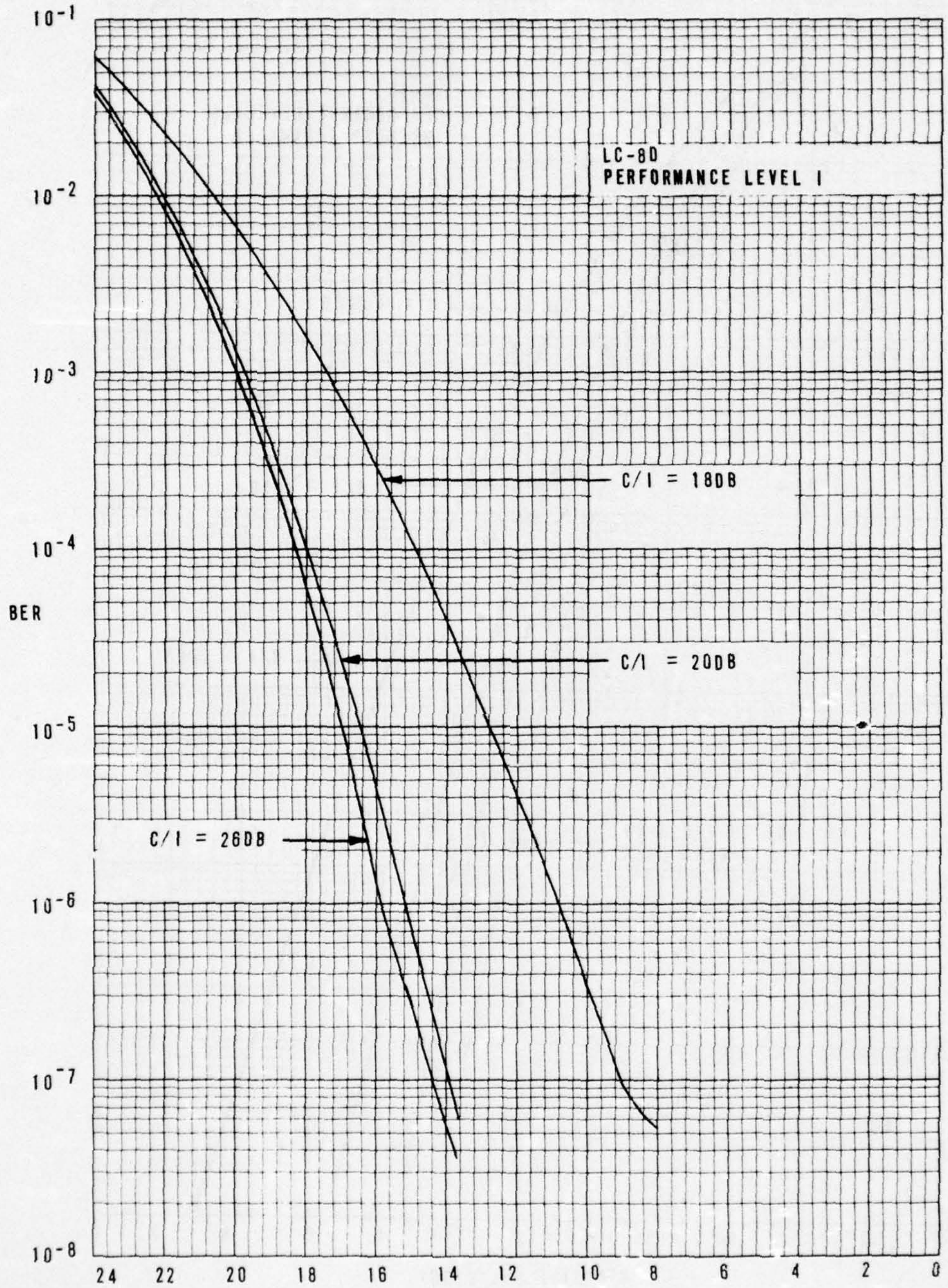


Figure 84
1X9.504MBPS BER VS CO-CHANNEL INTERFERENCE

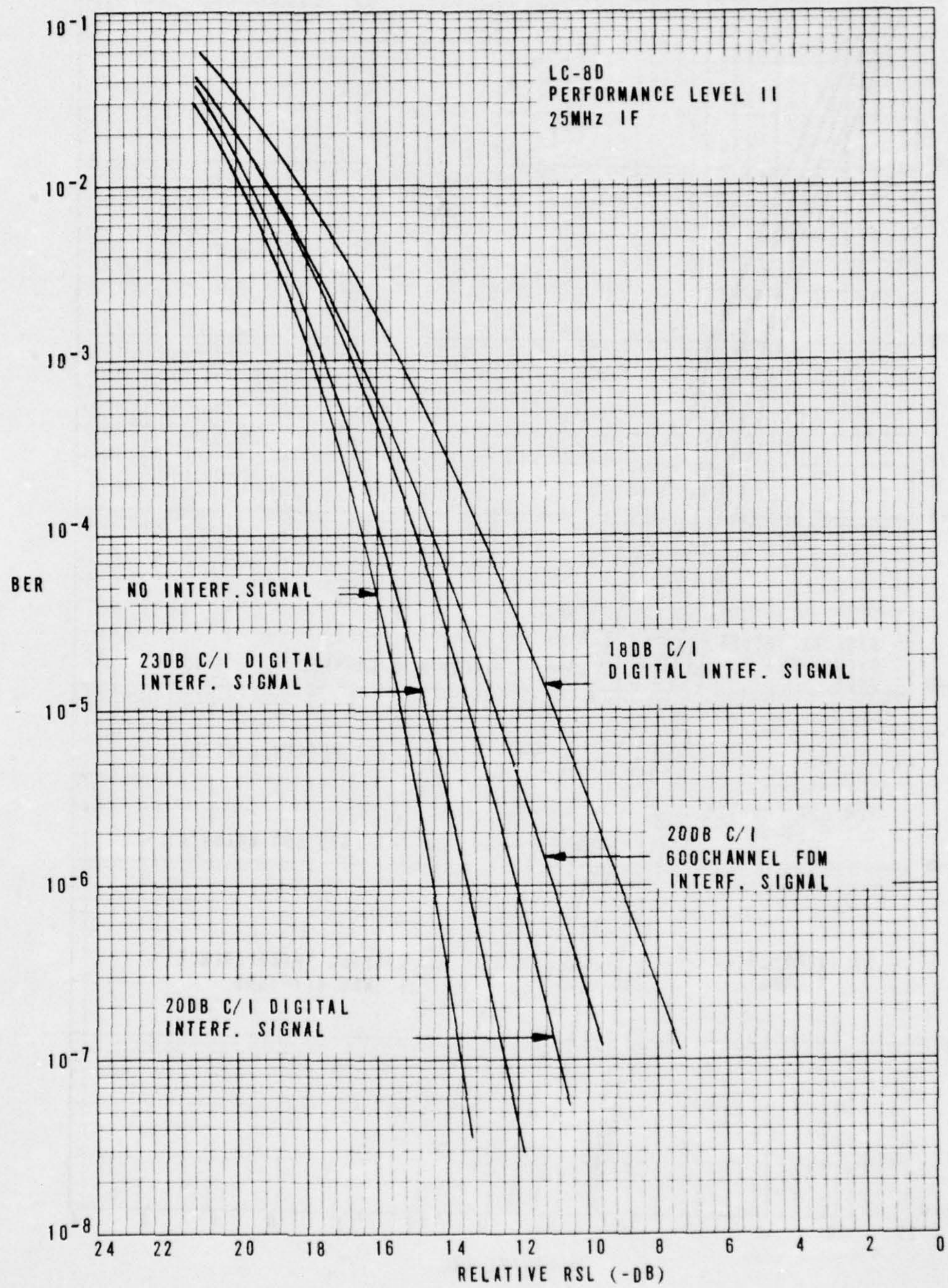
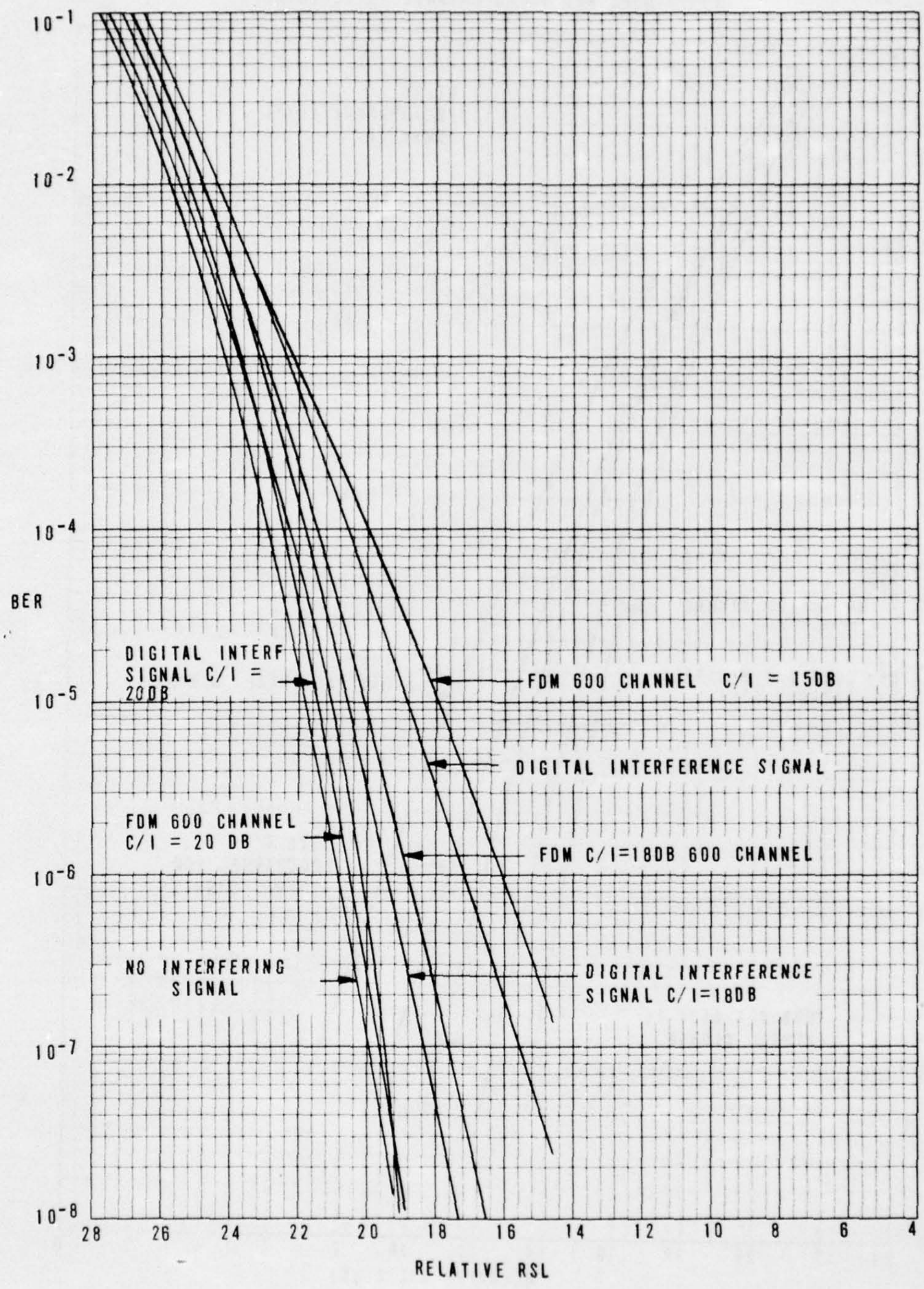


Figure 85

1X3.168MBPS BER VS CO-CHANNEL INTERFERENCE



for the same previously mentioned MBS rates and performance level combinations is presented in Figures 86 through 89 inclusive. The results are strongly dependent on the IF filter in the receiver.

4.6.8 Demultiplexer Frame Synchronization

During Phase 5, the DAU Acceptance Test, the Multiplexer and Demultiplexer units of the DAU were used for all of the DAU testing. Therefore, the primary function of the MUX/DEMUX to time division multiplex one or two message bit streams plus one service channel bit stream at the multiplicity of specified rates was repeatedly demonstrated. However, several tests were performed on the demultiplexer to demonstrate acquisition time, mean time to loss of acquisition, and time to declare loss of acquisition as these parameters would not normally show up in the DAU BER performance testing.

In order to measure the acquisition time and time to declare loss of acquisition, a special MUX test module was designed and constructed. This module was placed between the Multiplexer and Demultiplexer in a back-to-back configuration. The test module had the ability to be programmed to insert into the multiplexed data path a pseudo error rate between 2^{-1} and 2^{-15}. These pseudo errors were generated from a maximal length sequence generator 36 stages long or a sequence length of $2^{36}-1$ bits. Additionally, the multiplexed data stream could be inhibited with this module and it in conjunction with the demultiplexer was capable of yielding a pulse indicating sync acquisition time and time to declare loss of sync.

These two parameters were measured at the lowest possible data rate, one message bit stream at 3.168 Mbps, as this would yield the worst case times. Twenty measurements were taken at bit error rates of 2^{-8}, 2^{-9}, ..., 2^{-15} and at each BER the longest observed acquisition time was 20 milliseconds, well within the specification of 50 milliseconds with a 95 percent confidence level. Additionally, the time to recognize loss of sync which would commence on the inhibit of the MUX data, was between 0.2 and 0.4 ms. The sum of these two demultiplexer properties, 21 milliseconds, which would be the time to declare loss of sync and reacquire due to a loss of BCI is certainly within the 50 ms specification.

These two demultiplexer characteristics (declaration of loss of frame sync and declaration of frame sync) were measured and are presented as a dual trace oscilloscope photograph, Figure 90. Referring to the figure, the upper trace is derived from a function generator and is utilized to inhibit the multiplexer data output thus removing frame sync information to the demultiplexer. When this signal is high, the

Figure 86 A

2X12.672MBPS BER VS ADJACENT CHANNEL INTERFERENCE

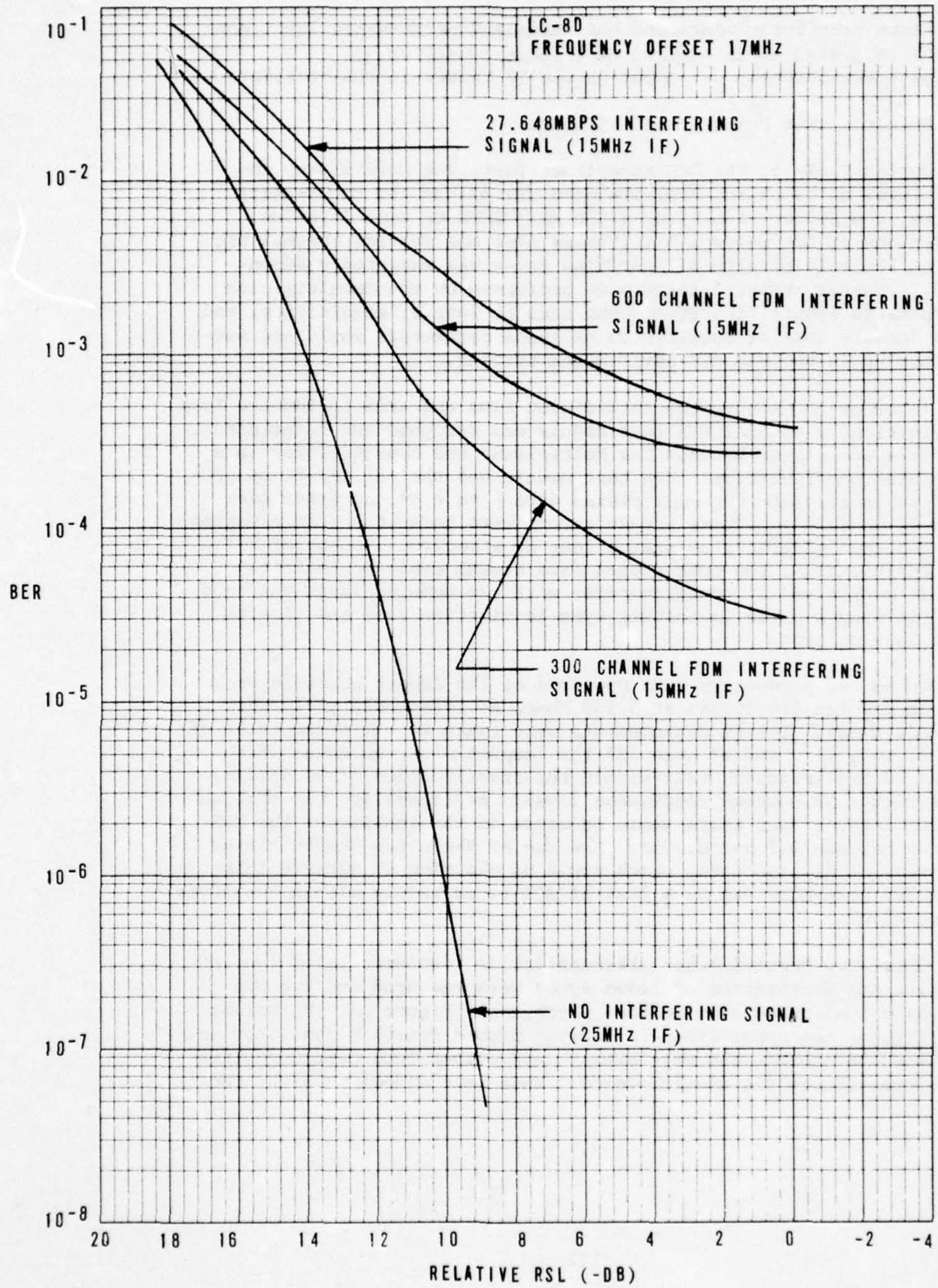


Figure 86 B

2X12.672MBPS BER VS ADJACENT CHANNEL INTERFERENCE

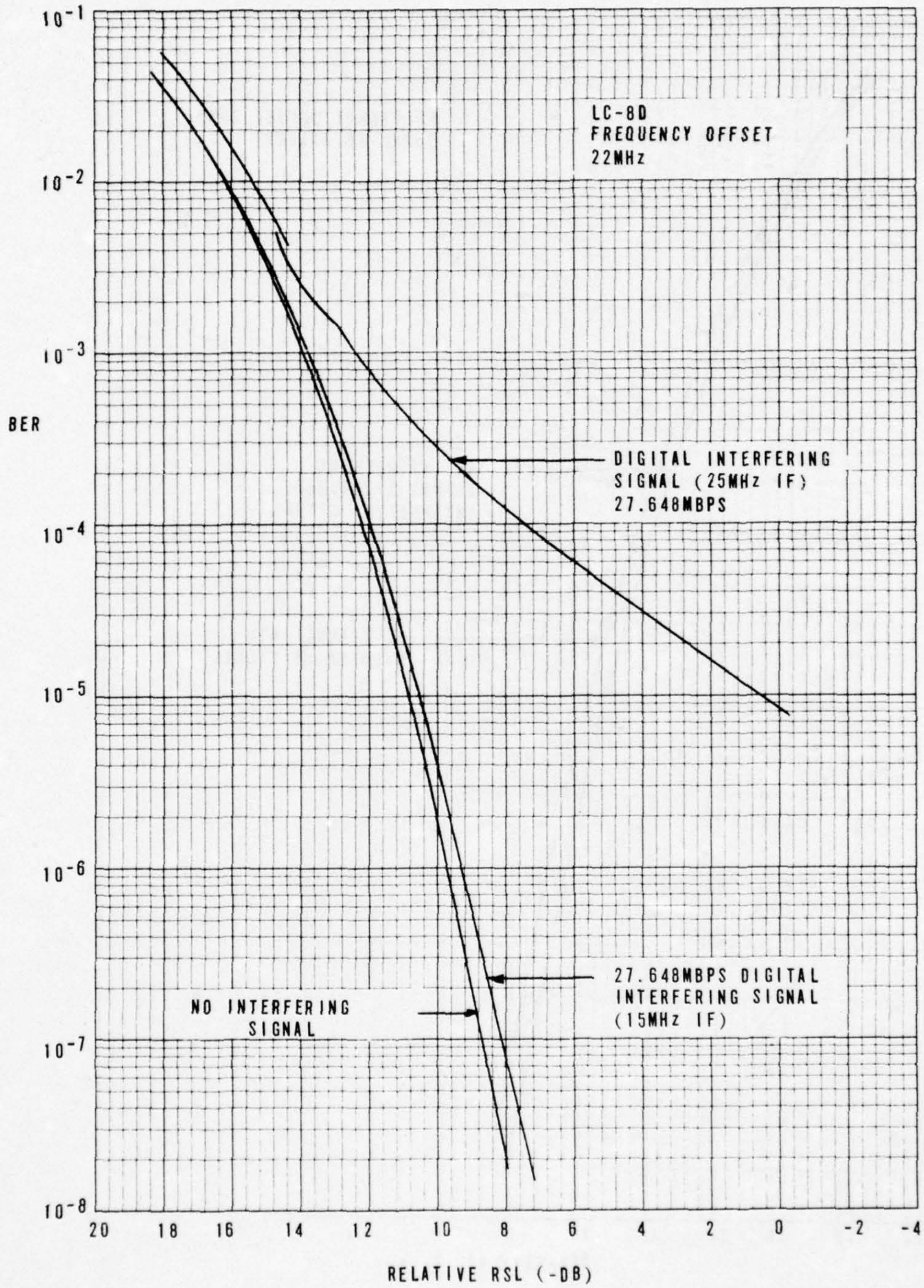


Figure 86 C

2X12.672MBPS BER VS ADJACENT CHANNEL INTERFERENCE

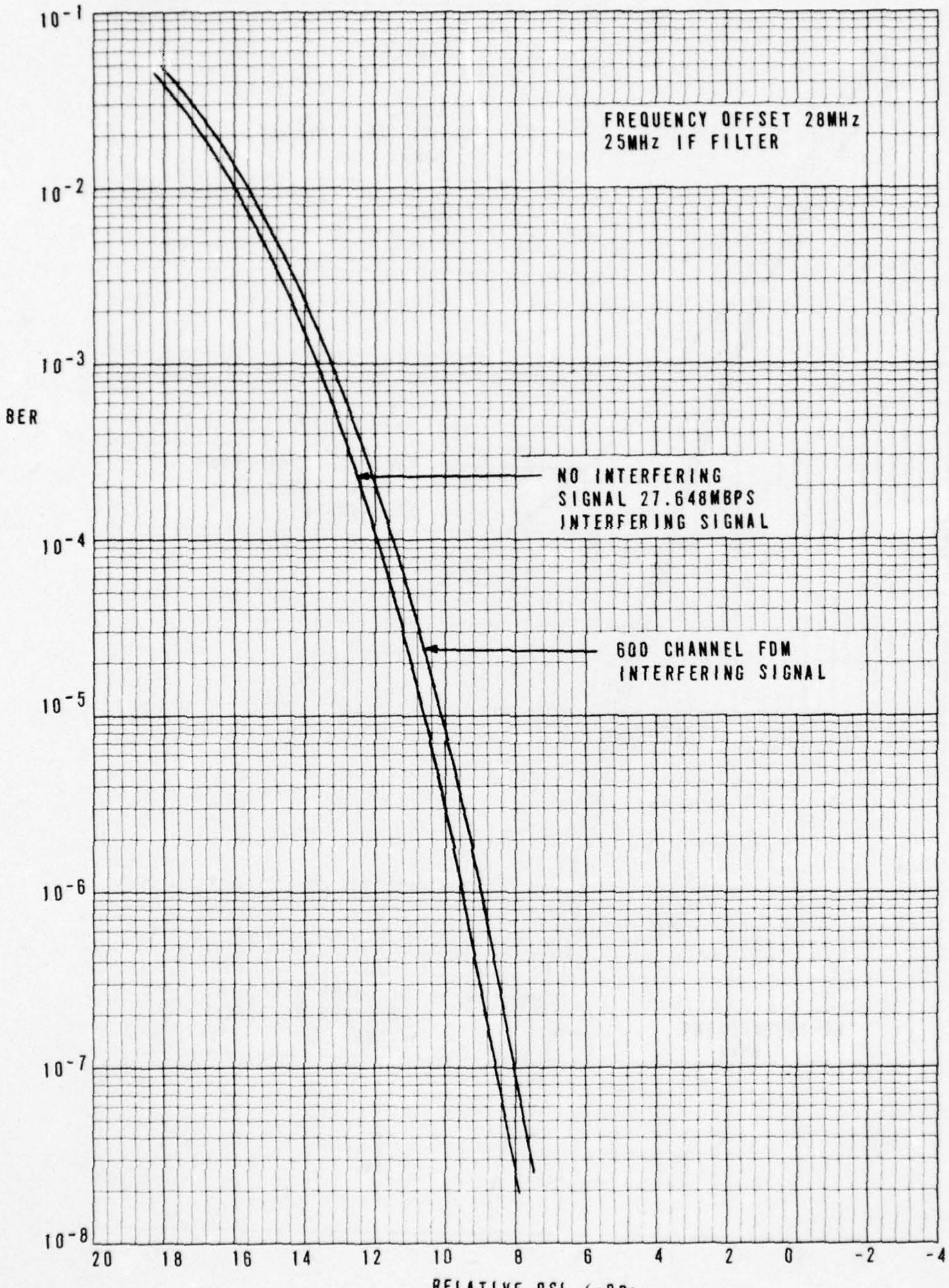


Figure 87A

1X12.672MBPS BER VS ADJACENT CHANNEL INTERFERENCE

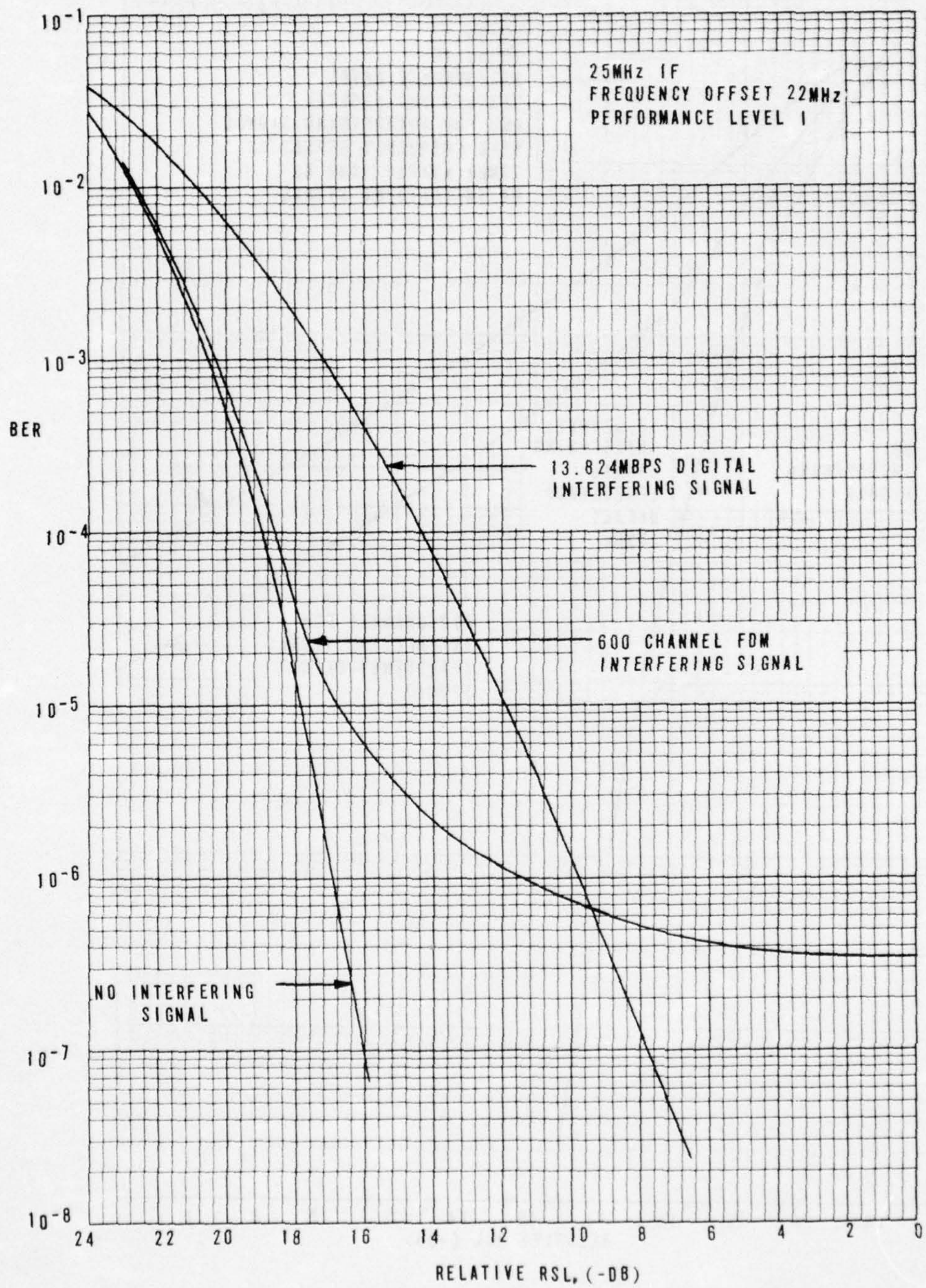
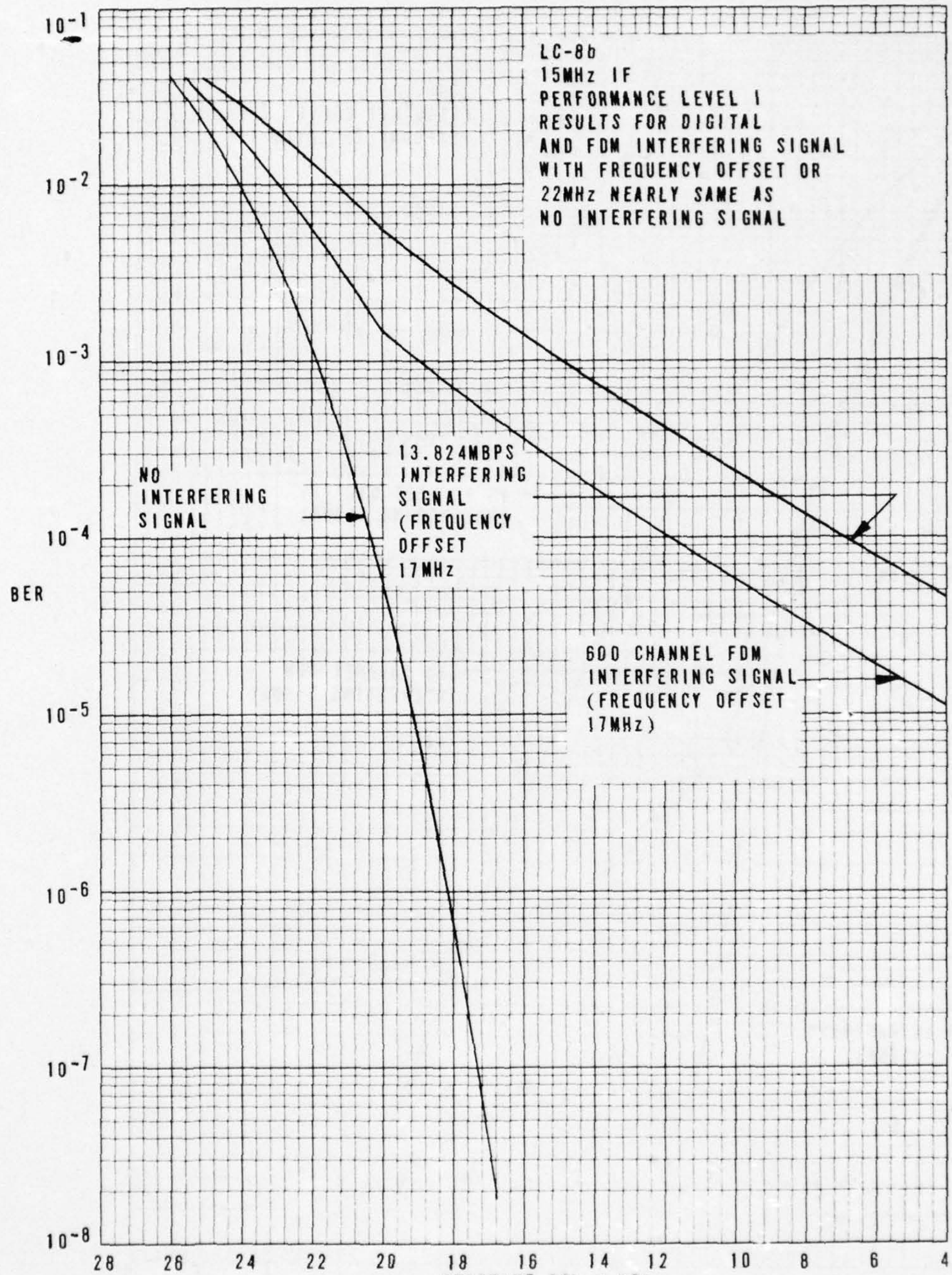


Figure 87 B

1X12.672MBPS BER VS. ADJACENT CHANNEL INTERFERENCE



AD-A032 014   AERONUTRONIC FORD CORP WILLOW GROVE PA RADIO TRANSMI--ETC F/G 17/2
MICROWAVE DATA TRANSMISSION TEST PROGRAM DIGITAL APPLIQUE UNIT.(U)
AUG 76 F A JESSEN, N G JONES, J W LAYER   F30602-73-C-0203

UNCLASSIFIED   RADC-TR-76-268   NL

3 OF 3
AD
A032014

END
DATE
FILMED
1-77

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Figure 88A

1X9.504MBPS BER VS ADJACENT CHANNEL INTERFERENCE

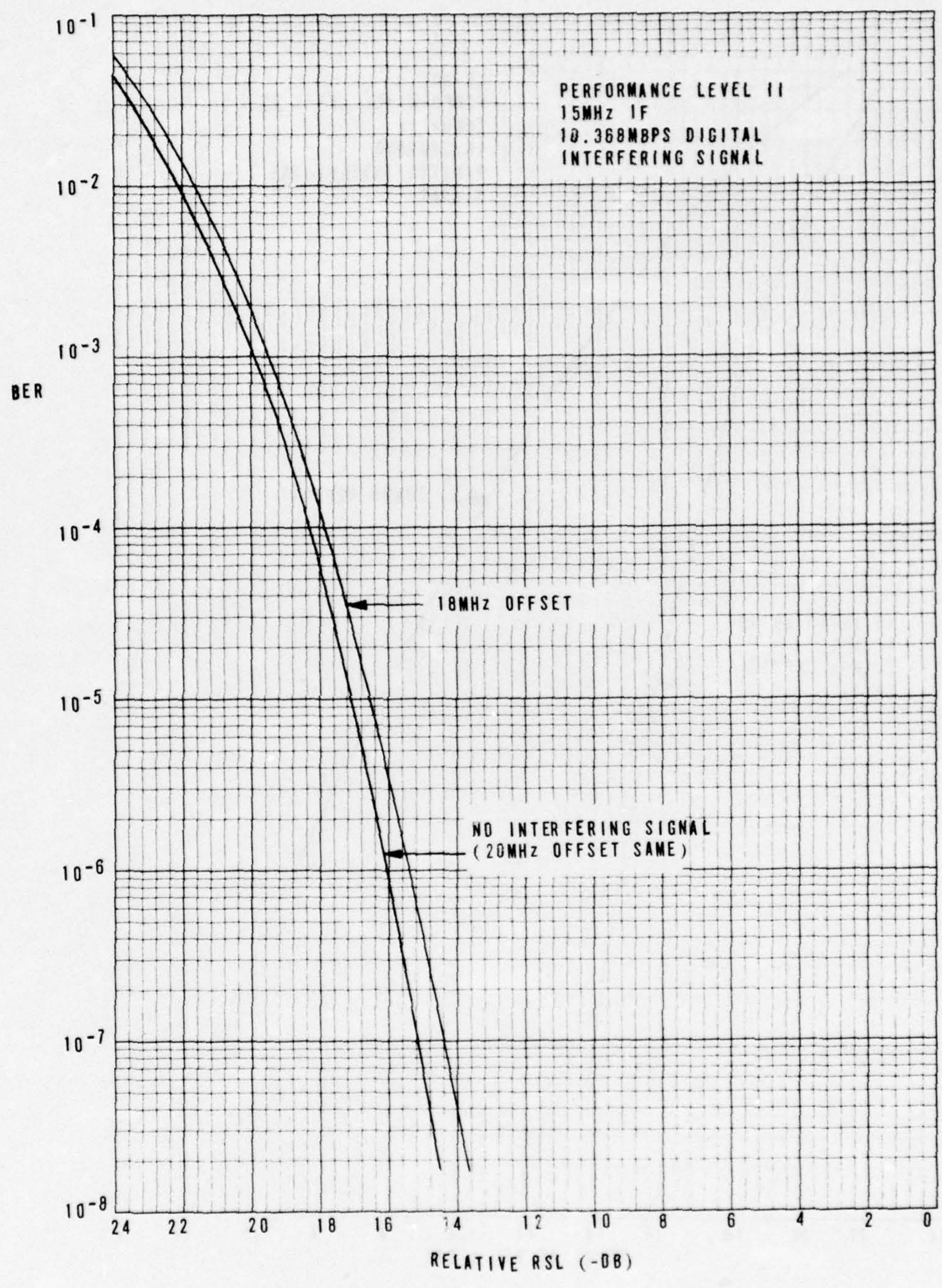


Figure 88B

1X9.504MBPS BER VS ADJACENT CHANNEL INTERFERENCE

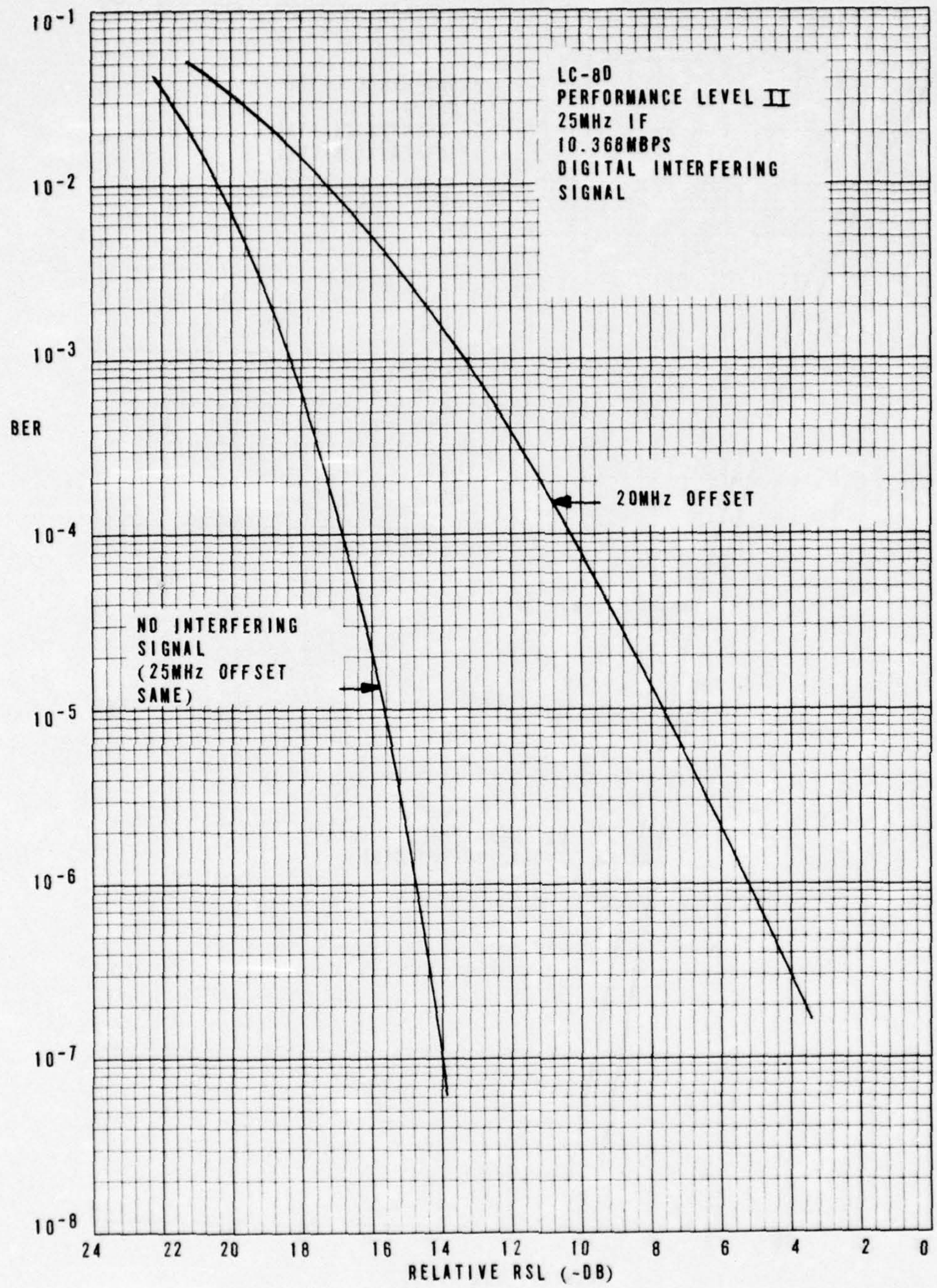


Figure 89 A

1X3.168MBPS BER VS ADJACENT CHANNEL INTERFERENCE

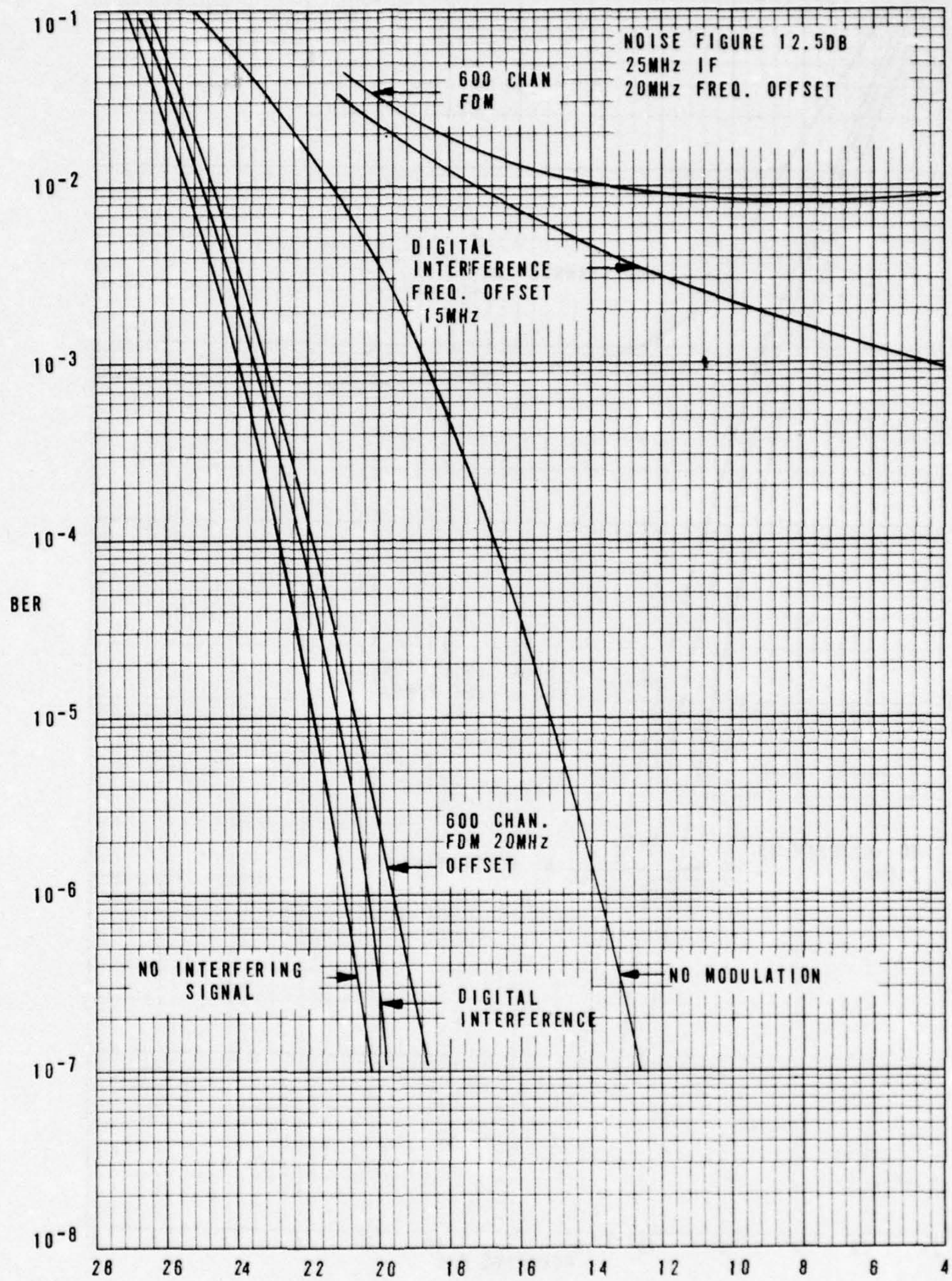


Figure 89B

1X3.168MBPS BER VS ADJACENT CHANNEL INTERFERENCE

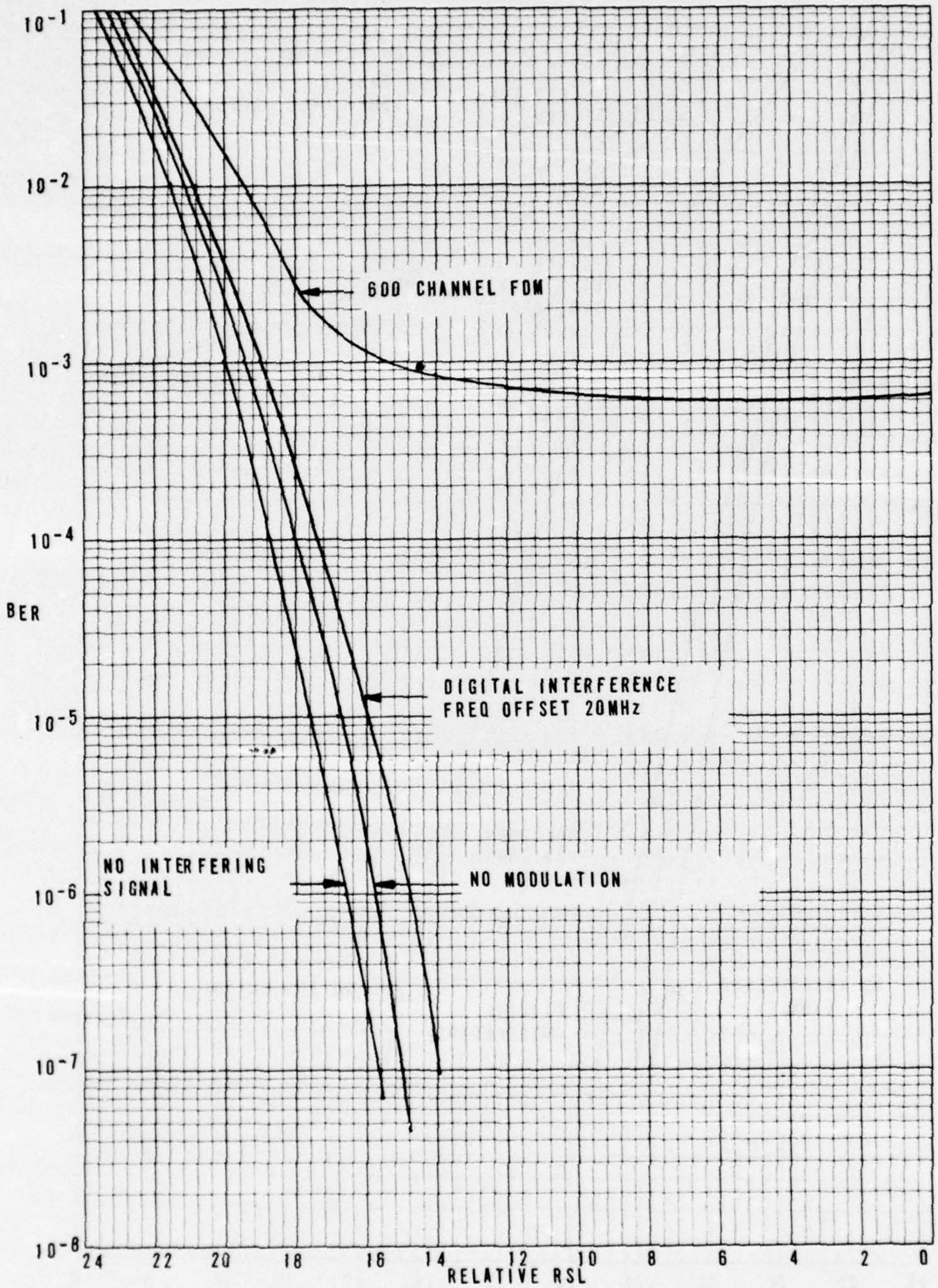
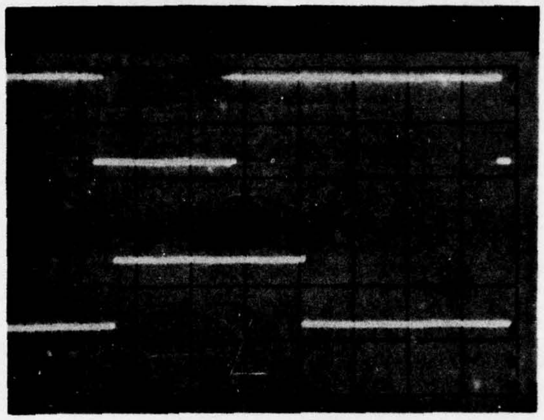


Figure 90
MUX SYNC TIME



TIME BASE: 1MS/CM
DATA RATE: 1MBS AT 3.168MBPS
ERROR RATE: 10^{-3}

TOP TRACE: INHIBIT SIGNAL
BOTTOM TRACE: MUX SYNC SIGNAL

data is inhibited while the low state permits the transmission of multiplexed data. The lower trace is the MUX Sync Output signal from the Receive Control module of the demultiplexer which indicates demultiplexer frame sync status (the high state indicating sync while the low state indicates no sync).

The oscilloscope was triggered on the positive going edge of the inhibit signal; therefore, the transition (enable to inhibit) is not visible. Notice that the sync signal is high at trace initiation, indicating frame sync, but that it drops to the low state, indicating loss of frame sync, in about 300 us. This sequence can also be observed at the next positive going transition of the inhibit signal. The time interval between the positive going edge of the inhibit signal and the high-to-low transition of the sync signal is a measure of the demultiplexer time to declare loss of frame sync.

Recalling that the low state of the inhibit signal allows multiplexed data to be transmitted to the demultiplexer and that the high state of the sync signal indicates sync acquisition, then the time interval between the high-to-low transition of the inhibit signal and the low-to-high transition of the sync signal is a measure of sync acquisition time. As illustrated in the figure, the sync acquisition time is about 1.5 ms. These tests were conducted at the lowest data rate since this condition should produce the longest time intervals.

During inactive testing periods (lunch time, nights, etc.), the demultiplexer was monitored for loss of frame sync at a system error rate of 10^{-2}. The accumulated time of this test was 48 hours (the longest segment being 14 hours) without any loss of frame sync.

4.6.9 Modem Switching

Figure 91 is a block diagram of the switching test configuration. Referring to the figure, the translated RF signal is divided to obtain two receiver signals. One signal is attenuated and then presented to the B radio receiver at a constant input level 3 dB above the RSL required to produce a BER of 10^{-7}. The second signal is subjected to linear amplitude modulation by a TWT prior to being applied to the A radio receiver at an input level that varies from 12.5 dB above to 12.5 dB below the RSL required to produce a BER of 10^{-7}.

The switching threshold and hysteresis levels of the three comparators (AGC, eye closure and out-of-band noise) on the performance monitor module were adjusted such that if the A radio RSL was less than 3 dB above the 10^{-7} RSL, the B radio was selected to be on line. Once

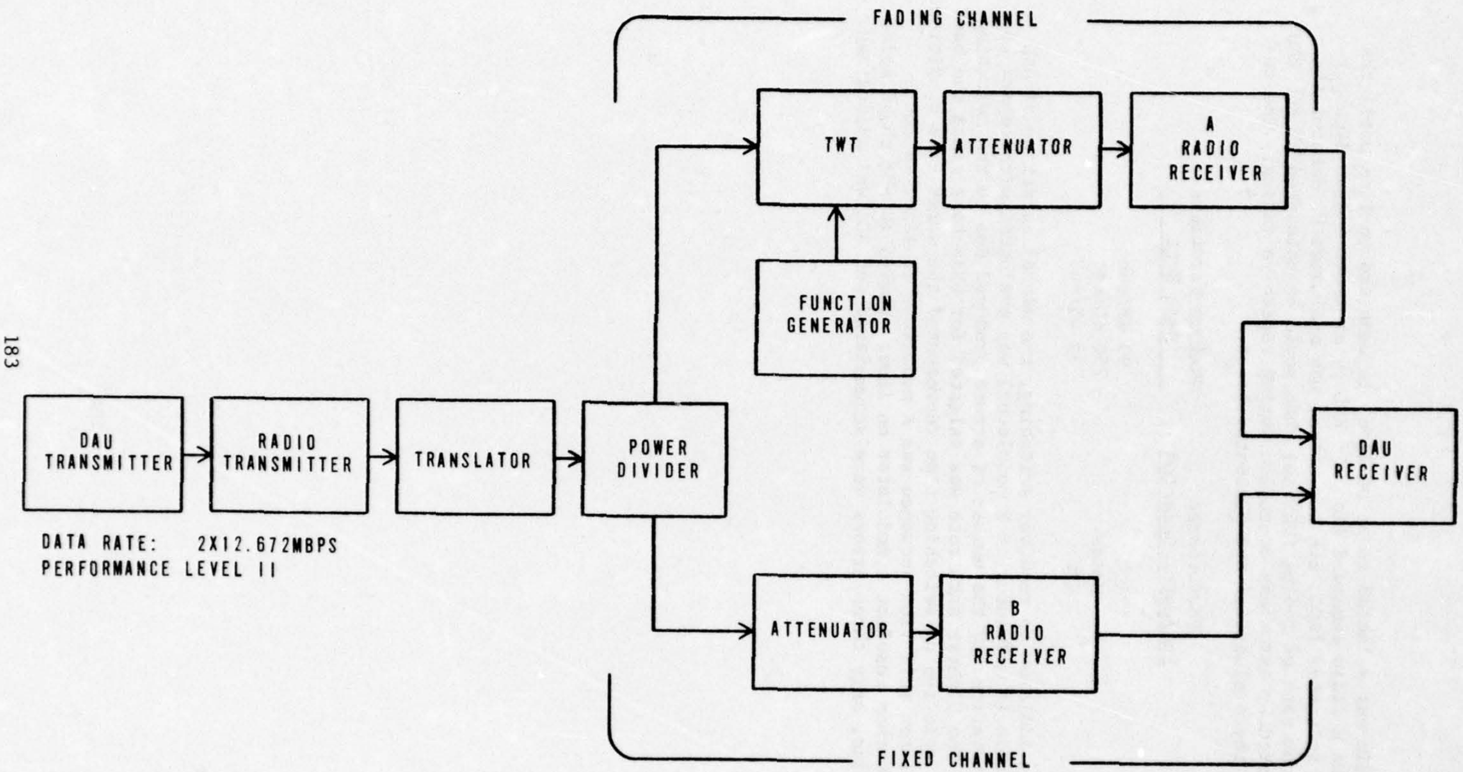


Figure 91

MODEM SWITCHING TEST BLOCK DIAGRAM

the B radio was selected to be on line, it remained on line until the RSL of the A radio exceeded its 10^{-7} RSL by at least 4 dB. Each performance indicator (AGC, eye and noise) was evaluated by determining the maximum rate of fading (dB/sec) that could be tolerated by the DAU as indicated by errorless operation during repeative fading. The results of the evaluations are presented below:

Performance Indicator Selected	Maximum Errorless Fade Rate
AGC	90 dB/sec
Noise	750 dB/sec
Eye	55 dB/sec

In addition to receiver switching, the manual selection of DAU transmitters (A modulator or B modulator) was evaluated with regard to BCI preservation and the number of errors produced due to the switching action. The highest data rate was selected for this test since the baud duration relative to switching time represented the worst case condition. The modulator selection sequence was A modulator on line, select B modulator then reselect A modulator on line. During 100 of these selection cycles, only three errors were accumulated and BCI was maintained.

SECTION 5

MICROWAVE RADIO MODIFICATIONS

5.1 INTRODUCTION

The DAU has been designed to interface with a wide variety of FDM FM type microwave radio sets. In order to achieve this design, several of the more commonly used radio sets have been evaluated to determine the interface and operational characteristics required between these radios and the DAU. The radios evaluated are listed below:

a. Aeronutronic Ford LC series
b. Collins AN/FRC-155, 156...162 type
c. Motorola AN/FRC 80 type
d. Lenkurt AN/FRC 109(V) type

Based on the evaluation conducted, it was concluded that the DAU can be operated satisfactorily with any of the radios mentioned with only minor modifications to the radios. It may be necessary to remove or by-pass several modules and functions not required for the DAU operation. These modules or functions are used in the analog mode of operation and are not required for the transmission of digital data. The modules or functions consist of such things as baseband filters, pilots, combiners, etc. In general the DAU requires a broadband baseband input to the transmitter section of the radio, a broadband baseband output from the receiver section of the radio, and a convenient point to sample the AGC voltage from the radio receiver IF amplifiers. The AGC voltage should have a positive sense with increasing signal strength. In the final design the AGC voltage may not be required; the diversity switching may be performed by out-of-band noise in the DAU receiver itself. All of the radios evaluated have the interface requirements mentioned.

To ensure a simple and easy integration of the DAU with any FDM/FM type radio, the following interface parameters for the radio would be established:

1.	Input impedance	75 ohm unbalanced
2.	Input sensitivity	10 MHz /volt

3.	Output impedance	75 ohm unbalanced
4.	Output sensitivity	1 volt/10 MHz
5.	Baseband response	Broadband limits of the radio
5.	AGC monitor (may not be required)	Neg. voltage preferable with positive sense for increasing RF signal level

In addition to the parameters tabulated above, the absolute delay between the two transmitters in a diversity radio and the absolute delay between the two receivers over the link must be measured during installation of the DAU. The difference in delay between the two transmitters more than likely is negligible, but if the delay is in excess of approximately 10 nanoseconds, then the delay should be compensated by selection of interconnecting cables, or the addition of a variable delay line. If the delay over the radio link including the receivers is excessive, the delay can be compensated in the DAU.

5.2 INTEGRATION OF THE DAU WITH THE AERONUTRONIC FORD LCT SERIES OF MICROWAVE RADIOS

The LCT series of equipments includes both Klystron remodulating terminals, heterodyne remodulating terminals, and heterodyne repeaters. The DAU has been tested with each type of equipment.

The modifications required to convert these equipments from FDM/FM transmission to digital transmission have been identified and are described in the paragraphs that follow.

5.2.1 Modifications to the Remodulating Heterodyne Terminals, Models LC-4D and LC-8D.

The basic configuration of the LC-4D and LC-8D is identical with the exception of the RF back plate which contains either 4 GHz or 8 GHz components. The module complement for each of these configurations is interchangeable and the nomenclature and handbook descriptions are the same.

To convert either terminal to digital transmission all baseband modules are removed which includes three modules on the transmitter and six on the receiver. The modules removed from the transmitter include the terminal filter module, 368-43020-11 Adder module, 368-42029-16, and the Dual pilot time detector, 368-43035-1. The modules removed from the receiver consist of the Dual Pilot Tone Detector 368-43035-1 terminal filter, 368-43020-12, noise amplifiers (2) 368-43018-1; and Baseband Combiner (Dual), 398-12040-1.

The DAU transmitter outputs are connected to the input (J1) of each deviator module 398-13665-1. Each radio terminal limiter/discriminator output (J2) on module 398-11470-10, is connected to the demodulator section of the DAU (Reference 5-1).*

The interface levels are those defined in Section 5.1. The Deviation sensitivity of the Deviator is 10 MHz/volt and the limiter discriminator is nominally 1 volt/10 MHz.

The AGC voltage connection are obtained at barrier strips located on the door of the radios. The AGC voltage for receiver A and B is obtained at terminal E 11 and terminal E 31 respectively (Reference 5-2). The AGC voltages are connected to the DAU and are used to activate the diversity switch.

5.2.2 Modifications to the LC-4G, LC-8G and LC-4N Heterodyne Repeaters

To modify a heterodyne repeater for digital transmission requires that five modules be added to the repeater configuration. A conversion kit which permits a repeater terminal to be reconfigured as a remodulating terminal was previously supplied in the form of spare modules which could be added to each equipment. The modules which must be provided and are included as part of the kit are:

2 Deviator Modules	P/N 398-13665-1
2 AFC Modules	P/N 368-42098-3
1 LIM/Discriminator	P/N 398-11470-10

One LIM/Discriminator module already exists with each repeater terminal as part of the FDM/FM drop-out capability; therefore, only one LIM/Discriminator module is included. After the repeater is reconfigured as a terminal, the interconnections described in paragraph 5.2.1 can be made. The only module removed from the repeater is an Insertion Amplifier, P/N 368-42028-13.

5.2.3 Modification to LCT Klystron Terminals LC-4A, LC-4E and LC-8E

The DAU has been operated with the LCT Klystron remodulating terminals and the modifications to these terminals identified. The modulator of the DAU is connected to the Klystron Driver, 368-43490-6, input J2. The outputs from the radio Limiter/Discriminator modules, 368-43489-6, at J2 on each unit are connected to the DAU demodulator (Reference 5A-1).

The AGC control voltage connections are found on the barrier strip located at the top of the radio rack. Channel A AGC voltage is available at 1 TB1 and Channel B voltage at 1 TB2 of the barrier strip (Reference 5A-2). Operating levels and impedances are those

* References for this Section are listed in Paragraph 5.6.

tabulated in Section 5.1. The modules removed from the Klystron terminals include the Adder, 368-42029-7; Terminal Filter, 368-43020-7; Dual Pilot Tone Detectors, 368-43035-1; Baseband Combiners, 395-12040-1; and Noise Amplifiers, 368-43018-1.

5.3 INTEGRATION OF THE DAU WITH THE COLLINS AN/FRC-155, 156...162 RADIOS

The recommended interface between the DAU and the AN/FRC-155, 156...162 radio sets would entail the connecting of the transmitter section of the DAU to the modulation amplifier of the radio set and connecting the output of the IF amplifier of the radio set to the input of the receiver section of the DAU. See Reference 1-1.

The transmit input J1 on the modulation amplifier can be used as an interface. J2 gets terminated. The deviation sensitivity of the radio transmitter is adjusted to 10 MHz/volt using the gain control R20 in the modulation amplifier. See Reference 1-2.

The receiver output J6 of the high level baseband amplifier module can be used as an interface. In each IF amplifier module, the de-emphasis network is by-passed. The demodulation sensitivity of the radio receiver is adjusted to 1 volt/10 MHz using gain control R4 in conjunction with the output pad at E24 and E25 if required. See Reference 1-3.

The AGC connection for each receiver can be made at J101 pin 22 also shown in Reference 1-3.

5.4 INTEGRATION OF THE DAU WITH THE MOTOROLA AN/FRC-80 RADIOS (MR 300)

The recommended approach for interfacing the DAU with the Motorola MR 300 entails connecting the transmitter section of the DAU to the input of the modulation amplifier and connecting the output of the IF amplifier of the radio set to the input to the receiver section of the DAU. See Reference 2-1. As with the Collins AN/FRC-155, 156...162, the IF amplifier module contains a limiter/discriminator stage, and the module output signal is actually the baseband output of the limiter/discriminator. The interfacing arrangement as recommended bypasses filter and pilot circuits, which are not considered essential for the transmission of digital data.

The transmit input 2 on the modulation amplifier can be used as an interface. Input 1 is terminated into 75 ohms. The deviation sensitivity of the radio transmitter is adjusted to 10 MHz/volt using the gain control R15 in the modulation amplifier. See Reference 3-1.

The receive output J3 or J4 on the IF amplifier module can be used as an interface. The demodulation sensitivity of the radio receiver is adjusted to 1 volt/10 MHz using gain control R58. See Reference 3-2.

The AGC control voltage connections are made at J1 Pin 9 for receivers A and B. All unnecessary baseband modules not used with the DAU application can be removed from the radio.

5.5 INTEGRATION OF THE DAU WITH THE LENKURT AN/FRC 109 RADIOS

The recommended interface between the DAU and the radio set entails connecting the transmitter section of the DAU to the input of the transmitter shelf and the output of the receiver shelf through an auxiliary amplifier module to the input to the receiver section of the DAU. See References 4-1 and 4-2. The radio interface levels are set to the nominal levels specified in Section 5.1. All unnecessary baseband modules not used with the DAU application can be removed from the radio.

The transmit input (75 ohm unbalanced) is accessible via pins 82 and 88 on the transmitter shelf can be used as the modulator input. See Reference 4-1. The deviation sensitivity of the radio transmitter is adjusted to 10 MHz/volt using the gain control R3 on the modulation amplifier board. See Reference 4-3.

The Radio receiver output is taken between pin A of J1 and ground or at connection J2 on the auxiliary amp board when the auxiliary amplifiers is configured for 75 ohms unbalanced. See Reference 4-4. The demodulation sensitivity of the radio receiver is adjusted to 1 volt/10 MHz using gain control R23 and level pads shown in Reference 4-5.

The AGC connections for each receiver is made at pin F of P3 as shown in Reference 5.

5.6 REFERENCES

REFERENCE 1	Department of the Army Technical Manual Operator, Organization, Direct Support and General Support Maintenance Manual for Radio Set AN/FRC-162 (V)(1-3)
Ref. 1-1	Signal Flow Block and Level Diagram, FO-2
Ref. 1-2	Schematic Diagram, Modulation Amplifier, FO-23
Ref. 1-3	Schematic Diagram, IF Amplifier, FO-17 (20F2)
REFERENCE 2	MR-300 RF Equipment Space Diversity Government Band Operation Supplement to Instruction Manual 68P85900A26
Ref. 2-1	Motorola Pt. No. 63E85938A86
REFERENCE 3	MR-300 Microwave Equipment
Ref. 3-1	MB158-1, Motorola Pt. No. 36A56-5
Ref. 3-2	MU572, Motorola Pt. No. 38A27-C
REFERENCE 4	Instruction Manual Lenkurt 76C1-39006 (MIL AN/FRC-109(V)) Microwave Terminal Assembly
Ref. 4-1	Section III, BL-39025(50F9)
Ref. 4-2	Section III, BL-39025(60F9)
Ref. 4-3	Section IV, EAS-28412-M1
Ref. 4-4	Section IV, EAS-37444-M1 (10F3)
Ref. 4-5	Section IV, EAS-28417-M1 (20F3)
REFERENCE 5	Technical Manual Microwave Radio Sets LC-4D, LC-4G, LC-8D and LC-8G T O. 31R5-4-135-2

Ref. 5-1	Chapter 8 FO-1, FO-9, Fig. 8-1
Ref. 5-2	Chapter 1 Figure 1-2 FO-13
REFERENCE 5A	LC-4A - T.O. 31R5-4-47-2 LC-4E - EL5820-792-14-TM LC-8E - NAVSHIPS 0967-326-4010
Ref. 5A-1	LC-4A - FO-7 sheet 2, FO-6, Fig. 6-1 and 6-2 LC-4E - EL5820-792-14-TM-27 LC-8E - 6WD3374, 6WD3407
Ref. 5A-2	LC-4A - FO-5 sheet 2, Fig. 2-2 LC-4E - EL5820-792-14-TM-44 LC-8E - 6WD3374, Fig. 5-6

SECTION 6

RELIABILITY ANALYSIS

6.1 OBJECTIVES

The objectives of the reliability analysis were to evaluate the mean time between repairs and the mean time between failures for non-redundant and redundant configurations of the DAU using the circuits and parts count of the feasibility model. The program goal for mean time between failure for a non-redundant configuration (containing all diagnostic, signal monitoring and switching functions required for a redundanct configuration) is 3500 hours. This goal was used to determine the required quality level of the components. Attainment of this goal requires use of MIL-SPEC components. With passive components and discrete semiconductor components at the minimum JAN quality level, the integrated circuits quality must be equivalent to Class C screening level, minimum, and one component type (a four-bit universal shift register) used in large quantity must be of Class A screening level. The analysis did not consider the possibility of Class B screening for all integrated circuits, but this quality perhaps could satisfy the program goal, and could also possibly provide cost savings as well.

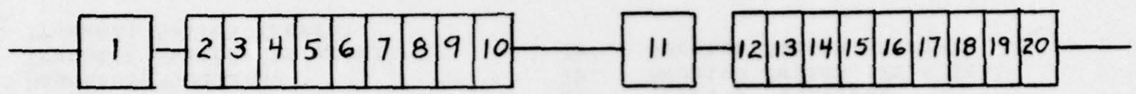
6.2 RELIABILITY MODELS

The reliability model for the single path (non-redundant) configuration is shown in Figure 92 . Although no redundant paths are present the Receive Switch, Performance Monitor, and Transmit Switch modules and all diagnostic indicator and signal monitoring circuits are included without distinction as to On-Line or Off-Line function.

The reliability model for the dual-path configuration is shown in Figure 93 . The Power Status modules are not shown as they contribute only to the Off-Line failure rate. For dual paths, no signal interruption occurs without simultaneous failures in the parallel paths. As a result, the failure rate for dual paths is calculated as the product of the failure rates for the two redundant paths. After all parallel paths have been reduced to equivalent single paths, the rate of failure to obtain signals through the redundant system is the sum of the failure rates of all of the series elements in the model. The rate of failure for determination of the mean time between component failures is the simple sum of the failure rates for each element in the model.

DAU TRANSMIT UNIT

DAU RECEIVE UNIT

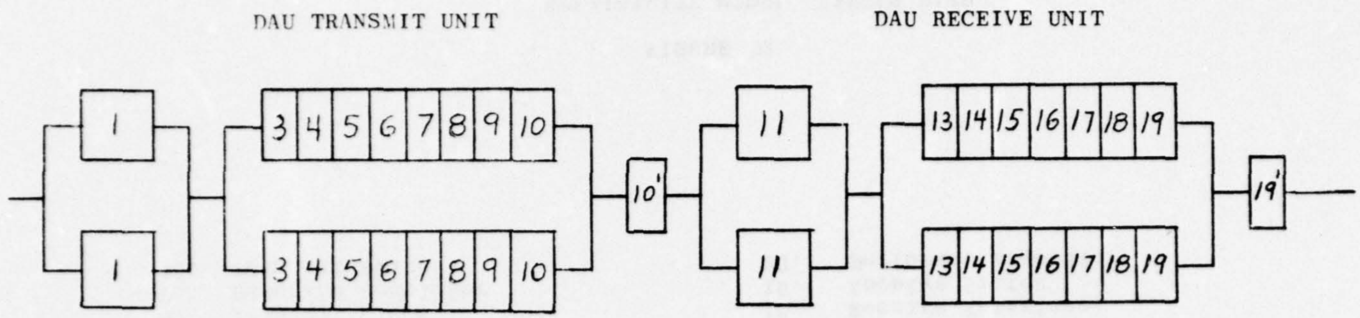


1. MUX Power Supply
2. Transmit Power Status
3. Transmit Timing
4. Transmit Control
5. Transmit Register
6. Transmit Interface
7. Data Input
8. Transmit Clock
9. Baseband Modulator
10. Transmit Switch

11. MODEM Power Supply
12. Receive Power Status
13. Baseband Demodulator
14. Receive Clock/Output
15. Receive Timing
16. Receive Control
17. Receive Register
18. Receive Interface
19. Receive Switch
20. Performance Monitor

FIGURE 92

RELIABILITY MODEL, SINGLE PATH
ON-LINE PLUS OFF-LINE



1. Mux Power Supply
3. Transmit Timing
4. Transmit Control
5. Transmit Register
6. Transmit Interface
7. Data Input
8. Transmit Clock
9. Baseband Modulator
10. Transmit Switch (Parallel)
10'. Transmit Switch (Serial)

11. Modem Power Supply
13. Baseband Demodulator
14. Receive Clock/Output
15. Receive Timing
16. Receive Control
17. Receive Register
18. Receive Interface
19. Receive Switch (Parallel)
19'. Receive Switch (Serial)

NOTE: Transmit and receive power status modules and performance monitor contribute only to off-line failures.

FIGURE 93

RELIABILITY MODEL, REDUNDANT PATHS AND SUPPLIES

6.3 CONDITIONS AND METHOD

The conditions taken for the reliability analysis are:

Environment:	Ground, Fixed
Ambient Temperature:	25°C
Internal Temperature Rise (Cabinet):	5°C
Circuit Module Temperature Rise:	10°C
Component Quality Level or Screening	
Microelectronics:	C, minimum
Discrete semiconductors:	JAN
Established reliability parts	
Capacitors:	L or M
Resistors:	M

The proposed quality levels for microelectronic components employs Class C screening for all but one component type. This type is required to pass Class A screening in order to meet a given MTBF requirement. Other quality level distributions among the components could be expected to meet the MTBF requirement. These have not been investigated, but may lead to a more cost-effective design.

The methods for estimating component failure rates are taken from MIL-HDBK-217B "Reliability Prediction of Electronic Equipment", edition of 20 September 1974. Failure rates for most components are calculated using the formulas, factors, and constants given in Section 2 of the above reference. The exception is the use of the generic failure rate from Section 3 of the above reference for RF coils and transformers. The RF coil failure rate was arbitrarily doubled for a variable RF coil. Maximum voltage stress or maximum power stress for any component is 0.3.

Rack and panel connectors, connected to the printed circuit boards by flexible leads, will be used in lieu of printed circuit card connectors. All components, with the exception of panel-mounted components, will be wave-soldered to the two-sided circuit boards. Panel-mounted components and card-mounted trimmer variable resistors will be hand-soldered to the boards using flexible leads. Strap-option connections will be made between turret lugs.

Failure rates for the MUX and MODEM power supplies, which will be purchased items, are specified as 5 percent per 1000 hours, or 50×10^{-6} per hour, for each triple supply, including current-steering diodes, load sharing, and voltage regulation circuits. Each supply is capable of independently supporting the dual MUX or dual MODEM equipment.

Failure rates for each plug-in module of the MUX and MODEM have been generated using component failure rates as described above and component counts obtained from the circuits of the feasibility model which has been delivered and tested. In some cases, a slight reduction in parts count has been made to reflect the difference in complexity between the equipment delivered, which can be switched between four separate data rates, and a production model which will be dedicated to a fixed data rate by strap option connections and/or change of oscillator fundamental frequencies.

Data containing the failure rates for 17 distinct plug-in modules which make up the MUX and MODEM of the DAU is shown in Table 15. The components of several plug-in modules are broken into ON-LINE (Serial), ON-LINE (Parallel) and OFF-LINE categories for individual computations illustrated subsequently.

6.4 SINGLE PATH MODEL

The ON-LINE and OFF-LINE failure rates of each plug-in module for the MUX and MODEM of the DAU, plus the failure rate of each of the two power supplies are summed in Table 16 . The total failure rate includes a large percentage of failures which will be non-relevant in the single path mode. The MTBF indicated at the bottom of the table exceeds the program goal of 3500 hours.

6.5 REDUNDANT PATH MODEL

The computation of an equivalent single-path failure rate for each parallel segment of the redundant path reliability model is given in Table 17.

The single-path and equivalent single-path failure rates for each serial segment of the redundant path reliability model is given in Table 18.

As expected, the rate of component failures (ON-LINE plus OFF-LINE) for the redundant-path model is greater, but somewhat less than double the rate for the single-path model. The Mean-Time-Between-Failures calculated for the redundant-path model is 1935 hours, compared with 3738 hours for the single-path model.

The rate of system outages for the redundant-path model is due exclusively to the two switches. The Mean-Time-Between-Outages calculated from these failure rates is an impressive 142,000 hours for the redundant-path model.

6.6 CONCLUSIONS

The redundant-path model of the DAU demonstrates that it is possible to employ automatic switching techniques to achieve a very impressive Mean-Time-Between-Outages using equipment constructed with less than the most stringent component quality screening procedures.

TABLE 15

SUMMARY OF MODULE FAILURE RATES

PLUG-IN MODULE	FAILURE RATE/10^6 HOURS			
	ON-LINE		OFF-LINE	QTY (DUAL)
	PARALLEL	SERIAL		
Power Status			1.4575	4
Transmit Timing	12.7255		0.6548	2
Transmit Control	12.2716			2
Transmit Register	11.0430			2
Transmit Interface	4.5815			2
Data Input	2.2710		1.0645	2
Transmit Clock	3.9395			2
Baseband Modulator	3.2912		2.6053	2
Transmitter Switch	2.9296	1.1519	3.0269	1
Baseband Demodulator	9.4193		14.2680	2
Rcvr Clock/Output	18.6303		3.4500	2
Receive Timing	17.1789		0.6554	2
Receive Control	12.2340		1.1322	2
Receive Register	4.5700		1.7657	2
Receive Interface	5.1528			2
Receive Switch	0.5349	5.8716	2.6893	1
Performance Monitor			5.4743	1
Mux Power Supply	50.0000			2
MODEM Power Supply	50.0000			2

TABLE 16. DAU MTBF FOR SINGLE SIGNAL PATH

		On-Line Plus Off-Line Failures/10^6 Hours
Transmit Unit		
	Power Supply	50.0000
	Power Status	1.4575
	Transmit Timing	13.3803
	Transmit Control	12.2716
	Transmit Register	11.0430
	Transmit Interface	4.5815
	Data Input	3.3355
	Transmit Clock	3.9395
	Baseband Modulator	5.8965
	Transmit Switch	7.1084
	Sub Total	113.0138
Receive Unit		
	Power Supply	50.0000
	Power Status	1.4575
	Baseband Demodulator	23.6873
	Receive Clock/Output	22.0803
	Receive Timing	17.8343
	Receive Control	13.3662
	Receive Register	6.3357
	Receive Interface	5.1528
	Receive Switch	9.0958
	Performance Monitor	5.4743
	Sub Total	154.4842
	Total	267.4980 per 10^6 hours

MTBF 3,738.3 Hours

TABLE 17-A

DAU TRANSMIT UNIT, REDUNDANT PATH MODEL

PLUG-IN MODULE	FAILURE RATE/10^6 HOURS			QTY
	ON-LINE		OFF-LINE	
	PARALLEL	SERIAL		
Power Status			1.4575	2
Transmit Timing	12.7255		.6548	2
Transmit Control	12.2716			2
Transmit Register	11.0430			2
Transmit Interface	4.5815			2
Data Input	2.2710		1.0645	2
Transmit Clock	3.9395			2
Baseband Modulator	3.2912		2.6053	2
Transmit Switch	2.9296	1.1519	3.0269	1
Single-Path sums	53.0529	1.1519	8.8090	
Dual-Path sums	106.1058	1.1519	14.5911	
Equivalent Series F.R.	0.0028	1.1519		

TABLE 17-B

DAU RECEIVE UNIT, REDUNDANT PATH MODEL

PLUG-IN MODULE	FAILURE RATE/10^6 HOURS			QTY
	ON-LINE		OFF-LINE	
	PARALLEL	SERIAL		
Power Status			1.4575	2
Baseband Demodulator	9.4193		14.2680	2
Receive Clock/Output	18.6303		3.4500	2
Receive Timing	17.1789		.6554	2
Receive Control	12.2340		1.1322	2
Receive Register	4.5700		1.7657	2
Receive Interface	5.1528			2
Receive Switch	0.5349	5.8716	2.6893	1
Performance Monitor			5.4743	1
Single-Path sums	67.7202	5.8716	30.8924	
Dual Path sums	135.4404	5.8716	53.6212	
Equivalent Series F.R.	0.0046	5.8716		

TABLE 17-C

DAU POWER SUPPLIES, REDUNDANT PATH MODEL

Mux Power Supply failure rate	$50/10^6$ Hrs, each
Equivalent Series failure rate	$.0025/10^6$ Hrs
MODEM Power Supply failure rate	$50/10^6$ Hrs, each
Equivalent Series failure rate	$.0025/10^6$ Hrs.

TABLE 18

DAU FAILURE RATES, REDUNDANT PATH MODEL

SERIES SEGMENT	PARALLEL CONTRIBUTION	SERIES CONTRIBUTION	GROSS (ON-LINE & OFF-LINE)
	$x10^{-6}$	$x10^{-6}$	$x10^{-6}$
Transmit Unit	0.0028	1.1519	121.8488
Receive Unit	0.0046	5.8716	194.9332
Mux Power Supply	0.0025	---	100.0000
Modem Power Supply	0.0025	---	100.0000
TOTALS	$0.0124x10^{-6}$	$7.0235x10^{-6}$	$516.7820x10^{-6}$

Sum of parallel and series contributions = $7.0359x10^{-6}$

Rate of system outages - 7.0359 per 10^{6} hours

Mean-time-between-outages = 142,128 hours

Rate of component failures = 516.78 per 10^{-6} hours

Mean-time-between-failures = 1935 hours

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

The results of this program indicate that the Digital Applique Unit (DAU) provides an expeditious and cost-effective means of converting analog radios carrying FDM/FM information to digital transmission. The DAU can be used effectively and efficiently in any FDM/FM system configuration meeting DCS transmission requirements. All design goals of this program were achieved. Specifically, the bit error rate versus received signal level performance requirement was satisfied for a 99 percent RF bandwidth efficiency of 2 Bps/Hz.

The experimental phase of the DAU program indicated that a modified form of quaternary modulation which yielded a controlled spectrum is superior to conventional quaternary modulation and Class I or Class IV partial response modulation techniques. The primary design goal of realizing 2 Bps/Hz at a BER of 10^{-7} at a C/N of 27 dB (E_b/N_o = 24 dB) where C/N is measured in a half bit rate bandwidth was achieved. Baseband BER vs. baseband S/N measurements indicated the 4 level modem was operating close to the theoretical limit.

Tests at Fort Huachuca on an AN/FRC-162 and AN/FRC-80 demonstrated that the modem is capable of being interfaced with standard type FDM/FM radios with minimum modifications. No alignment or modification of these radios was performed, except for disabling the squelch. The disabling of the squelch was necessary because it squelched at too low an RSL for some tests. The relatively inferior BER vs. E_b/N_o results for the AN/FRC-80 were attributed largely to the limited frequency response of the radio. No attempt was made to compensate for the poor frequency response of the radio by modifying the modem because of the time limitations and the gross misalignment of the radio. The AN/FRC-162 was interfaced with the modem/DAU without any difficulty whatsoever.

The preliminary tests indicated that the DAU which included transmit and receive switches and performance assessment but not the MBS-SCRS mux met the design goals. The performance assessment was predicated on eye closure, out-of-band noise and AGC voltage. The receiver switch which is of the hitless type compares the channel status and selects the better channel when both channels are near threshold as well as when one channel is far superior to the other.

To effectively handle propagation fades, such as frequency selective fades, the performance assessment reaction time is on the order of hundreds of dB per second based upon out-of-band noise measurements. The switch reaction time due to the eye monitor is slower than for the OBN, but this condition can be rectified by a relatively simple modification. The eye pattern monitor was not designed to be of a high speed but to merely detect radio degradation. However, the eye closure monitor has the potential for having faster response times than either OBN or AGC. Further work should be conducted in the switch area, particularly in improving the speed of the eye closure monitor.

Acceptance tests on a Diversity Modem (no MBS-SCBS mux) at the Aeronutronic Ford facility were performed to demonstrate basic modem operation such as interface levels, switching, etc. Two standards were used for developing performance criteria for the DAU, the RADC statement of work and the AN/FRC-163 specification. Subsequently, the diversity modem was tested over an LC-8D at RADC. The ability of the DAU to compensate for a non-ideal baseband frequency response was demonstrated as part of the testing effort. In addition, radio degradations such as IF group delay, baseband non-linearity, and residual FM, were introduced to ascertain the DAU performance for these conditions. The test results indicated that a large amount of distortion compared to a normal FDM radio was required to cause a relatively small degradation in BER vs. RSL.

When the MBS-SCBS Mux was completed, the entire DAU was tested at RADC with the LC-8D radios. Tests were performed at mission bit stream rates from 3.168 Mbps to 25.344 Mbps at two performance levels (i.e., assigned bandwidths as given in *Table 13*). *BER vs.* E_b/N_o vs. IF filter tests indicated that enhanced performance could be obtained at the lower data rates by the use of relatively narrow filters. BER vs. E_b/N_o *as a function of radio* degradation measurements attested to the robustness of the DAU/radio. BER vs. co-channel interference tests indicated that approximately a 23 dB carrier-to-interference ratio can be tolerated with a small BER vs. E_b/N_o degradation. Adjacent channel (equal amplitude interfering signal) interference tests indicated that the minimum frequency separation tolerable is a function of the receiver IF filter. Both of these types of interference tests are quite severe and represent a situation which should never occur to this degree in an operational system.

The performance assessment test data indicated that a degrading channel can be detected well before the BER of 10^{-7} threshold is reached, especially at the lower rates, using the OBN monitor. The OBN monitor performance exceeded expectations, but two areas of improvement remain. The noise slot monitored was at a frequency of 13.170 MHz, which was

selected for 26.112 Mbps operation (the first spectral null occurs at 13.056 MHz). This value of frequency for the OBN slot was far from an optimum choice at the other rates, especially the lowest rates. Although the present OBN monitor appears to be more than satisfactory, a greater range of linear operation and greater sensitivity could be obtained by having the noise monitor frequency follow the data rate. A second area of improvement is switching and monitor indication based upon the logarithm of the noise (i.e., linear in dB rather than voltage). A breadboard circuit to perform this function has been built but has not been tested with the DAU. The above cited modifications should make the OBN linear over a very wide RSL range.

The eye closure monitor worked satisfactorily over an RSL range corresponding to approximately 6 dB above that level which yielded a BER of 10^{-7} to a level corresponding to a very high BER. In addition, the eye closure monitor, unlike the other monitors, responds to channel degradations which produce intersymbol interference. As was mentioned previously, the response time of the eye closure monitor should be improved. The eye closure and OBN monitors are complementary and work well over a wide range of RSL and contribute to good diversity operation. An additional performance assessment input would be framing BER from the MBS-SCBS demultiplexer although this is not considered to be essential.

Although the DAU met all applicable requirements, there are several areas of refinements which may be considered beyond those already mentioned. First, logic families other than ECL should be evaluated for the DAU. Although ECL is capable of extremely high speed and had good termination characteristics, it is at a disadvantage when compared to some logic such as low power Schottky TTL in power consumption and cooling. A mixture of logic families may be optimum.

A second refinement would be construction of a final "brassboard" prior to productization. Although the critical portions of the DAU are operating satisfactorily and the design was laid out for printed circuit, a "brassboard" could prevent production problems. The brassboard should include mechanical refinements. Presently, the DAU (with non-redundant mux) is contained in four main frames. However, many modules and the mux main frames are lightly loaded and could be condensed. The optimum mechanical packaging probably would be two larger main frames and one or two smaller power supply frames for a complete DAU including a redundant MBS-SCBS mux/demux.

Built-in test equipment (BITE) has been largely incorporated into the present DAU but can be increased somewhat. The BITE outputs as well

as the normal channel status outputs (failures, performance assessment, etc.) should be brought out for remote telemetry purposes. This would permit remote fault isolation of a DAU at an unattended site.

The present clock averaging technique in the modem provides for a dynamic delay in the radio receivers of plus and minus one quarter of a modem data bit (this could be readily extended to $\pm 1/2$ bit) without error and without loss of BCI. Additionally, there exists a gradual change in clock phase with the switching of modem receivers. As a minimum, investigation should be made into the diversity switching after demultiplexing and its impact on clock averaging and tolerance to greater dynamic delay. If greater dynamic delay tolerance is desired than is affordable by clock averaging at the multiplexer output, then a bit spreading (i.e., elastic buffer) technique, which is not presently employed, may be investigated. This technique, if applicable, could provide a dynamic delay tolerance only limited by the degree of spreading provided.

APPENDIX A

ERROR RATE PERFORMANCE

A-1 INTRODUCTION

In paragraph 4.6.2 of this report the Bit Error Rate vs. Received Signal Level data obtained during the Phase 5, Acceptance Test effort is presented in nine figures (Figures 47, 48-A, 48-B, 49, 50-A, 50-B, 51, 52 and 53) and encompasses a variety of MBS rates, several IF bandwidths and two bit packing density values. In order to facilitate the assessment of the error rate performance of the DAU for the various operational constraints, a comparison of the theoretically predicted performance and the empirically obtained data is presented as an appendix to the final report.

Before proceeding with the comparison of the theoretical and empirical data, it is of interest to note that the summary of the measured error rate performance data presented in Tables A-1 and A-2 was obtained by RADC personnel several months after completion of the Phase 5 Acceptance Test effort. A comparison of this data with that presented in Figures 47, 48-A, 48-B, 49, 50-A, 50-B, 51, 52 and 53 attests to the operational stability and repeatibility of the DAU equipment.

A-2 DATA SUMMARY

Tables A-1 and A-2 contains the error rate performance data of the DAU for Performance Level conditions I (1 bps/HZ) and II (2 bps/HZ) respectively. Specifically the tables contain the Eb/No (dB) and RSL (-dBm) values corresponding to observed error rates of $5x10^{-9}$ and $1x10^{-2}$ as a function of both the total MBS rate and the IF bandwidth. As can be noted in the tables total MBS rates of 3.168, 6.336, 9.504, 12.672, 19.008 and 25.344 Mbps were employed for the error rate performance measurement effort. It should also be noted that the error rate performance of the DAU was determined for three values of IF bandwidth; 10 MHz, 15 MHz and 25 MHz.

A-3 THEORETICAL PERFORMANCE

According to Mazo [(1)] et al the probability of error of an N-level FSK signal for large signal-to-noise ratio and small deviation ratio ($\Delta F/N < 1/2$) is given by

(1) Rate Optimization for Digital Frequency Modulation, J.E. Mazo, Harrison E. Rowe and J. Salz, Bell System Technical Journal, November 1969, pp 3021 to 3029.

Table A-1. Performance Level I Error Rate Data

MBS INPUT RATE (MBPS)	NUMBER OF INPUTS	TOTAL MBS RATE (MBPS)	P_e	BW = 10 MHz		BW = 15 MHz		BW = 25 MHz	
				RSL (-dBm)	Eb/No (dB)	RSL (-dBm)	Eb/No (dB)	RSL (-dBm)	Eb/No (dB)
3.168	1	3.168	1×10^{-2}	84.1	11.9	81.7	14.3	78.0	18.0
			5×10^{-9}	78.0	18.0	75.2	20.8	69.9	26.1
3.168	2	6.336	1×10^{-2}	81.2	11.8	80.4	12.6	77.7	15.3
			5×10^{-9}	75.1	17.9	73.2	19.8	70.6	22.4
9.504	1	9.504	1×10^{-2}	80.6	10.6	80.1	11.1	77.9	13.3
			5×10^{-9}	73.0	18.2	73.2	18.0	70.9	20.3
12.672	1	12.672	1×10^{-2}	80.6	9.4	80.4	9.6	79.0	11.0
			5×10^{-9}	70.6	19.4	73.0	17.0	71.4	18.6

Table A-2. Performance Level II Error Rate Data

MBS INPUT RATE (MBPS)	NUMBER OF INPUTS	TOTAL MBS RATE (MBPS)	P_e	BW = 10 MHz		BW = 15 MHz		BW = 25 MHz	
				RSL (-dBm)	Eb/No (dB)	RSL (-dBm)	Eb/No (dB)	RSL (-dBm)	Eb/No (dB)
3.168	2	6.336	1×10^{-2}	74.4	18.6	74.4	18.6	71.8	21.2
			5×10^{-9}	66.6	26.4	66.9	26.1	63.4	29.6
9.504	1	9.504	1×10^{-2}	77.7	13.5	77.2	14.0	75.5	15.7
			5×10^{-9}	69.2	22.0	70.0	21.2	68.7	22.5
12.672	1	12.672	1×10^{-2}	74.1	15.9	73.0	17.0	73.3	16.7
			5×10^{-9}	65.5	24.5	65.4	24.6	65.7	24.3
9.504	2	19.008	1×10^{-2}	N/A	N/A	70.4	17.8	70.2	18.0
			5×10^{-9}			62.1	26.1	61.1	27.1
12.672	2	25.344	1×10^{-2}	N/A	N/A	N/A	N/A	71.5	15.5
			5×10^{-9}					62.4	24.6

$$P_e = \frac{1}{\sqrt{2\pi\rho}} \frac{\cot\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)}{\sqrt{\cos\left(\pi\frac{\Delta f}{N}\right)}} \epsilon^{-2\rho\sin^2\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)} \tag{A-1}$$

where

Δf = level separation
N = symbol rate
p = RF signal-to-noise ratio in frequency band B_c
B_c = Bandwidth according to Carson's rule
$B_c = N + (n-1)\Delta f$

However, according to the results of simulations performed by CNR[(2)] for a quaternary format (2 bits/sec/HZ) a filter bandwidth of 1.125 times the bit rate was found to be optimum. This conclusion is compatible with the results of empirical evaluations conducted by Aeronutronic Ford. As a consequence, in the ensuing presentation, the probability of error equation, as given by A-1 will be utilized as indicated with the exception that the optimum RF bandwidth as defined by CNR will be employed in lieu of Carson's bandwidth.

The ratio of the energy per bit to the noise power density can be expressed as

$$\frac{E_b}{N_o} = \frac{1}{2}\rho BT \tag{A-2}$$

where

T = symbol Interval = $\frac{1}{N}$

B = Noise Bandwidth

Solving for p, we obtain.

$$\rho = 2\frac{E_b}{N_o}\frac{1}{BT} = 2\frac{E_b}{N_o}\frac{N}{B} \tag{A-3}$$

Substituting equation A-3 into equation A-1 yields

$$P_e = \frac{1}{\sqrt{2\pi}} \frac{\cot\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)}{\sqrt{\cos\left(\pi\frac{\Delta f}{N}\right)}} \frac{1}{\sqrt{\rho}} \epsilon^{-4\frac{E_b}{N_o}\frac{N}{B}\sin^2\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)} \tag{A-4}$$

(2) Line of Sight Techniques Investigations, CNR Inc., RADC-TR-74-330, Final Report, January 1975, p 4-14.

Re-arranging terms we obtain

$$P_e = \frac{\cos\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)}{\sqrt{\pi \cos\left(\pi\frac{\Delta f}{N}\right)}} \; \frac{\epsilon^{-4\frac{E_b}{N_o}\frac{N}{B}\sin^2\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)}}{\sqrt{4\frac{E_b}{N_o}\frac{N}{B}\sin^2\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)}} \qquad \text{(A-5)}$$

It is, of course, recognized that frequency modulation/demodulation is a non-linear process and the signal-to-noise ratio at the output of the demodulator is a function of the pre-detection carrier-to-noise radio as well as the deviation ratio. Therefore, one would intuitively expect that the error rate performance of a system employing n-level FSK modulation techniques would also be a function of the pre-detection carrier-to-noise ratio and the deviation ratio. In equation A-5, the impact of the carrier-to-noise ratio and the deviation ratio on the error rate performance is explicity defined by the N/B and $\sin^2(\pi\Delta f/2N)$ terms respectively. It, therefore, appears reasonable to define an effective energy per bit to noise power density ratio, such that

$$\left(\frac{E_b}{N_o}\right)_e = \frac{N}{B}\sin^2\left(\frac{\pi}{2}\frac{\Delta f}{N}\right)\frac{E_b}{N_o} \qquad \text{(A-6)}$$

where E_b/No is the energy per bit to noise power density ratio conventionally defined for linear modulation system (equation A-2). Based on the above definition, a given Eb/No value will yield a specific Pe provided the $N/B\sin^2(\pi\Delta f/2N)$ product is maintained at a constant value.

It was established during the optimization of a quaternary baseband modem that for a 26.4 Mbps input mission bit stream, a 6.3 MHz p-p frequency deviation yields a bit packing density of 2 bits/sec/HZ in a 99 percent energy bandwidth. Therefore, we can write

$$\frac{\Delta f}{N} = \frac{6.3\times10^6/3}{26.2\times10^6/2} = 0.1591 \qquad \text{(A-7)}$$

The above value of Af/N represents the upper bounds of the deviation ratio required to achieve a packing density of 2 bits/sec/Hz , independent of the total MBS rate.

Substituting Af/N = 0.1591 into equation. A-5 yields an expression

for the probability of bit error, applicable to 2 bits/sec/Hz packing density performance conditions.

$$P_e = \frac{0.5835}{\sqrt{(0.2447)(N/B)(E_b/N_o)}} \in^{-(0.2447)(N/B)(E_b/N_o)} \quad \text{(A-8)}$$

Letting B = (1.125) (2N), we obtain:

$$P_e = \frac{1.7694}{\sqrt{E_b/N_o}} \in^{-0.1088 E_b/N_o} \quad \text{(A-9)}$$

A plot of equation A-9 is presented in Figure A-1. Also presented in Figure A-1 is a plot of BER vs. Eb/No for performance level I (1 bit/sec/Hz) operating conditions. For the latter plot, the probability of error expression given by equation A-10 was employed.

$$P_e = \frac{1.4492}{\sqrt{E_b/N_o}} \in^{-0.2427 E_b/N_o} \quad \text{(A-10)}$$

In the deviation of equation A-10, Af/N was set equal to 0.3500 and the optimum RF bandwidth was chosen to be equivalent to that used for the performance Level II expression; i.e. B = (1.25) (2 N).

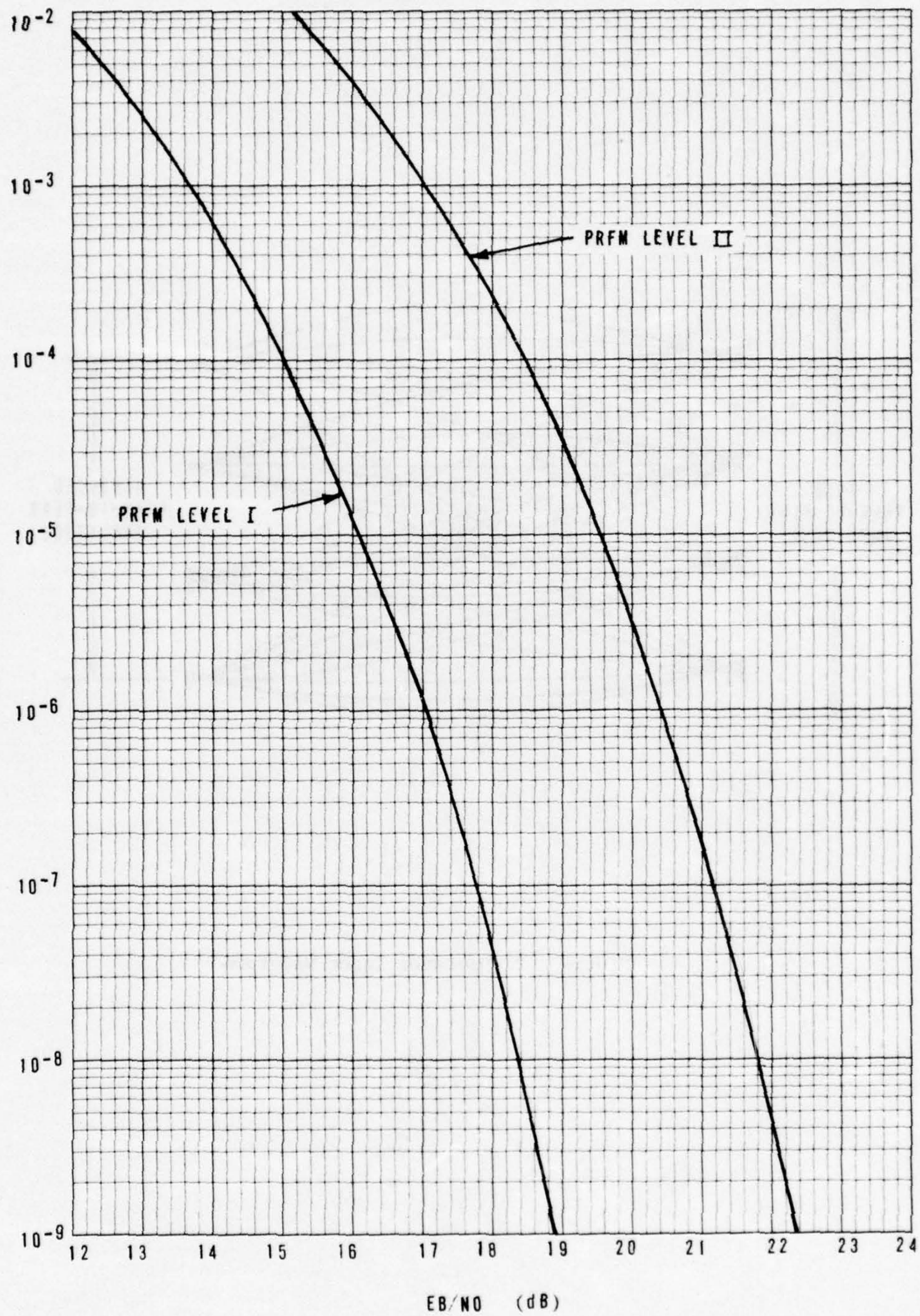
A-4 DEVIATION RATIO CONSIDERATIONS

The procedure used to determine the peak to peak frequency deviation for the error rate performance measurements encompassed the determination of that amplitude of deviator input signal which resulted in a specific RF bandwidth efficiency factor. Since the deviation sensitivity of the deviator was known the corresponding peak-to-peak frequency deviation was readily determinable from the amplitude of the deviator input signal.

The input to the deviator was, of course, a four level baseband waveform, of the form depicted in Figure A-2. In order to ensure repeatability of measurements the amplitude of the deviator input waveform was defined as the peak-to-peak voltage of the outer levels at the cross-over points. The peak-to-peak amplitude of the deviator input waveform at times other than the cross-over points is on the average greater than the peak-to-peak amplitude at the cross-over points. It is estimated that the true peak-to-peak amplitude of the deviator input waveform is approximately twenty percent greater than the peak-to-peak amplitude observed at the cross-over points. As a consequence the peak-

Figure A-1

THEORETICAL BER VS. E_b/N_o (LIM/DISC DETECTION)



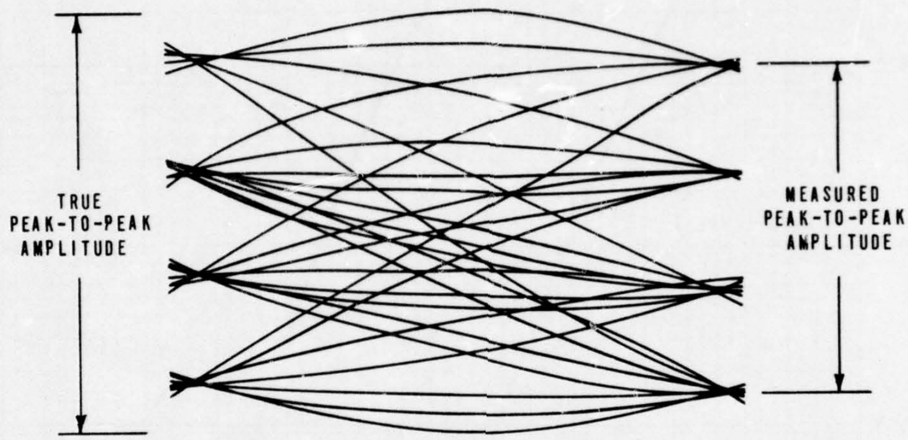


Figure A-2 Deviator Input Waveform

to-peak frequency deviation values used in the ensuing discussion will be modified to reflect this consideration. Table A-3 summaries the modifications to the measured peak-to-peak frequency deviations for the various MBS rates. The deviation ratio as herein used is defined as the ratio of the level separation in frequency to the symbol rate

$$\frac{\Delta f}{N} = \frac{\Delta F/3}{N} \qquad \text{(A-11)}$$

A-5 PERFORMANCE LEVEL II DATA

The measured performance level II BER vs. Eb/No data for total MBS rates of 6.336, 9.504, 12.672, 19.008 and 25.344 Mbps is presented in Figures A-3 through A-7 inclusive. The measured data is presented in dotted lines for easy identification. Also included in the figures are the theoretically predicted performance for the optimum IF bandwidth, and where applicable IF bandwidths of 10, 15 and 25 MHz.

In all of these figures the degradation in error rate performance due to the use of IF bandwidths greater than the optimum value is evident. The manifestation of the larger IF bandwidth is a reduction in the pre-detection carrier-to-noise ratio and consequently a reduction in the signal-to-noise ratio of the recovered baseband waveform. Since the decision process performed by the by the baseband demodulator is a function of the baseband signal-to-noise ratio the degradation of the error rate performance with increasing IF bandwidth is to be expected

Also evident in the BER vs. Eb/No figures is the degradation of error rate performance due to the use of IF bandwidths which are smaller than the optimum value. This behavior is attributed to the loss or attenuation of spectral components which are essential to the faithful reconstruction of the message waveform. The loss of signal energy due spectral truncation apparently cannot be adequately compensated for by the attendant reduction in the pre-detection noise level.

Referring to Figure A-3 (2x3.168 MBPS), it can be noted that measured performance closely approximates the predicted performance for both values of IF bandwidth (15 MHz and 25 MHz). This behavior is as anticipated since both IF bandwidths exceed the optimum bandwidth value of 7.776 MHz. The slope of both error rate curves do, however, suggest the presence of intersymbol distortion, which may be due to the less than ideal phase characteristics of the IF filters.

Table A-3. Modified Deviation Ratio Values

TOTAL MBS RATE (MBPS)	PRFM LEVEL	SYMBOL RATE -N ($x 10^6$)	MEASURED		MODIFIED	
			ΔF p-p ($x 10^6$)	$\frac{\Delta f}{N}$	ΔF p-p ($x 10^6$)	$\frac{\Delta f}{N}$
3.168	I	1.7280	1.83	0.3530	2.20	0.4236
6.336	I	3.4560	3.07	0.2961	3.68	0.3553
9.504	I	5.1840	4.42	0.2842	5.30	0.3410
12.672	I	6.9120	7.07	0.3410	8.48	0.4092
6.336	II	3.4560	1.23	0.1186	1.48	0.1423
9.504	II	5.1840	3.09	0.1987	3.71	0.2384
12.672	II	6.9120	2.77	0.1336	3.32	0.1603
19.008	II	10.368	3.33	0.1071	4.00	0.1285
25.344	II	13.824	6.35	0.1531	7.62	0.1837

Figure A-3

BIT ERROR RATE VS E_b/N_o (2x3.168 MBPS) - PRFM LEVEL II

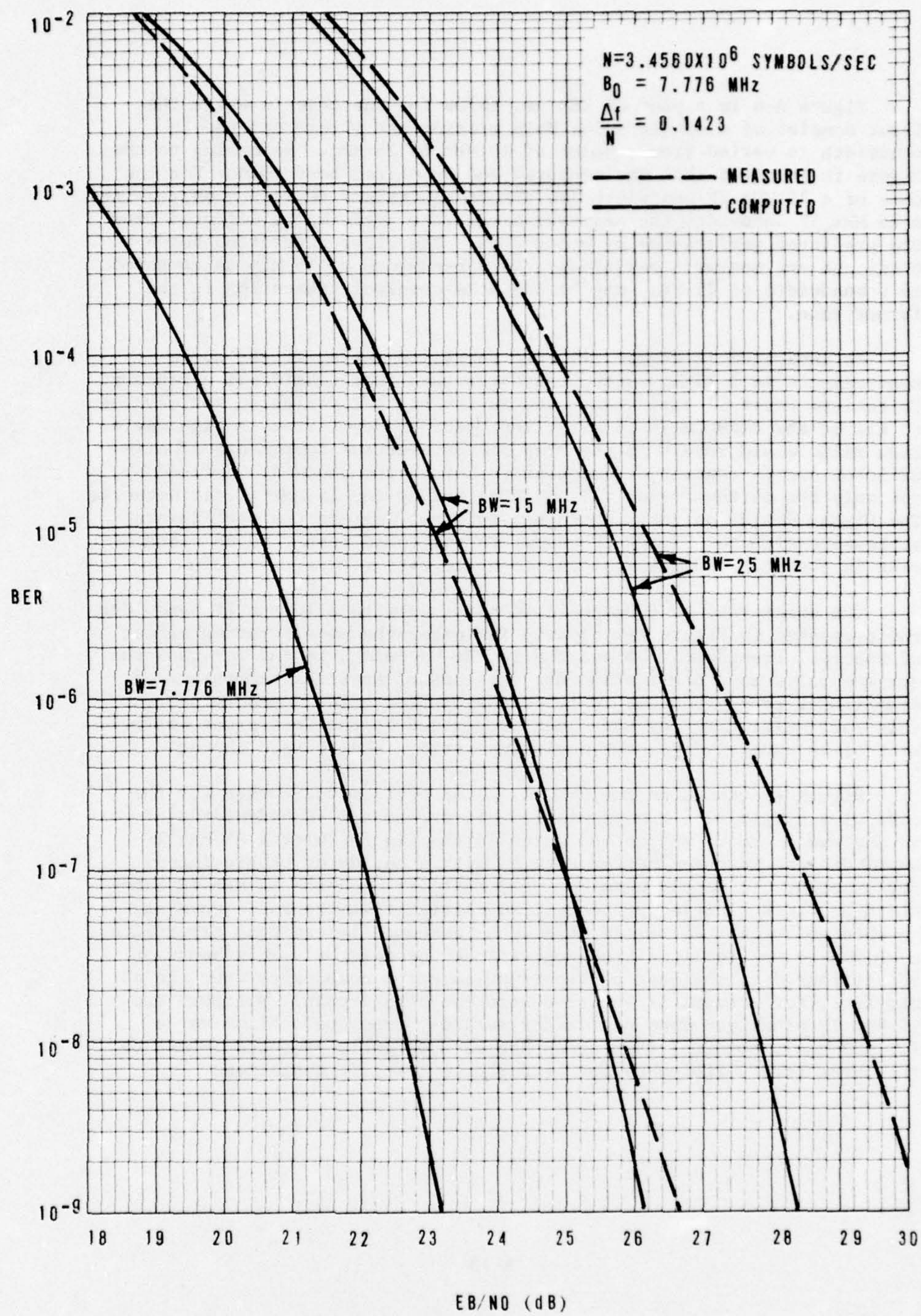


Figure A-4 is a plot of BER vs. Eb/No for the case in which the input consist of a single 9.504 MBPS mission bit stream and the IF bandwidth is varied from a value of 10 MHz to 25 MHz. Referring to the figure it is noted that the measured and predicted performance for the case of a 25 MHz IF bandwidth are almost equivalent (within ½ dB). With a 15 MHz IF bandwidth the measured error rate performance differed from the predicted performance by about 2 dB. The wider separation between predicted and measured performance at a bandwidth of 15 MHz as compared to a bandwidth of 25 MHz, may be due some spectral truncation in the former case.

As indicated in Figure A-4, the deviation ratio for the above measurements is 0.2384, which is greater than that considered necessary to achieve Level II performance and is the highest deviation ratio value of all of the PRFM Level II error rate performance tests. A high deviation ratio would result in the presence of spectral components of significant energy content at frequencies beyond the bandwidth defined by not only the optimum value (11.664 MHz) but by the 15 MHz filter network. The higher deviation ratio would not only not degrade the performance achievable with the 25 MHz IF bandwidth but could result in an enhancement in the post detection signal-to-noise ratio.

The error rate performance data obtained with a 10 MHz IF bandwidth and presented in Figure A-4 clearly indicates the deteriorating effect of spectral truncation. Since the 10 MHz bandwidth is smaller than the optimum value some degradation due the loss of spectral components of significant energy content is to be anticipated. The degradation, for this particular case may have been compounded by the inadverent employment of an excessively large deviation ratio, as discussed above.

Figure A-5 contains the BER vs. Eb/No performance curves for the case of a single 12.672 Mbps mission bit stream and IF bandwidths of 15 MHz and 25 MHz. As can be noted in the figure, with a 25 MHz IF bandwidth the measured performance is within one dB of thepredicted performance. It should also be noted that although the 15 MHz IF bandwidth provides a higher pre-detection carrier-to-noise ratio than can be obtained with a 25 MHz IF bandwidth, essentially the same error rate performance was realized with both filter bandwidths. This behavior is attributed to the loss of important spectral components when the 15 MHz IF filter network is inserted into the signal path. Although the 15 MHz IF bandwidth does not differ markedly from the optimum value (15.552 MHz), spectral truncation has an apparently profound impact on the error rate performance for performance level II operation.

Figure A-4

BIT ERROR RATE VS E_b/N_o (1x9.504 MBPS) - PRFM LEVEL II

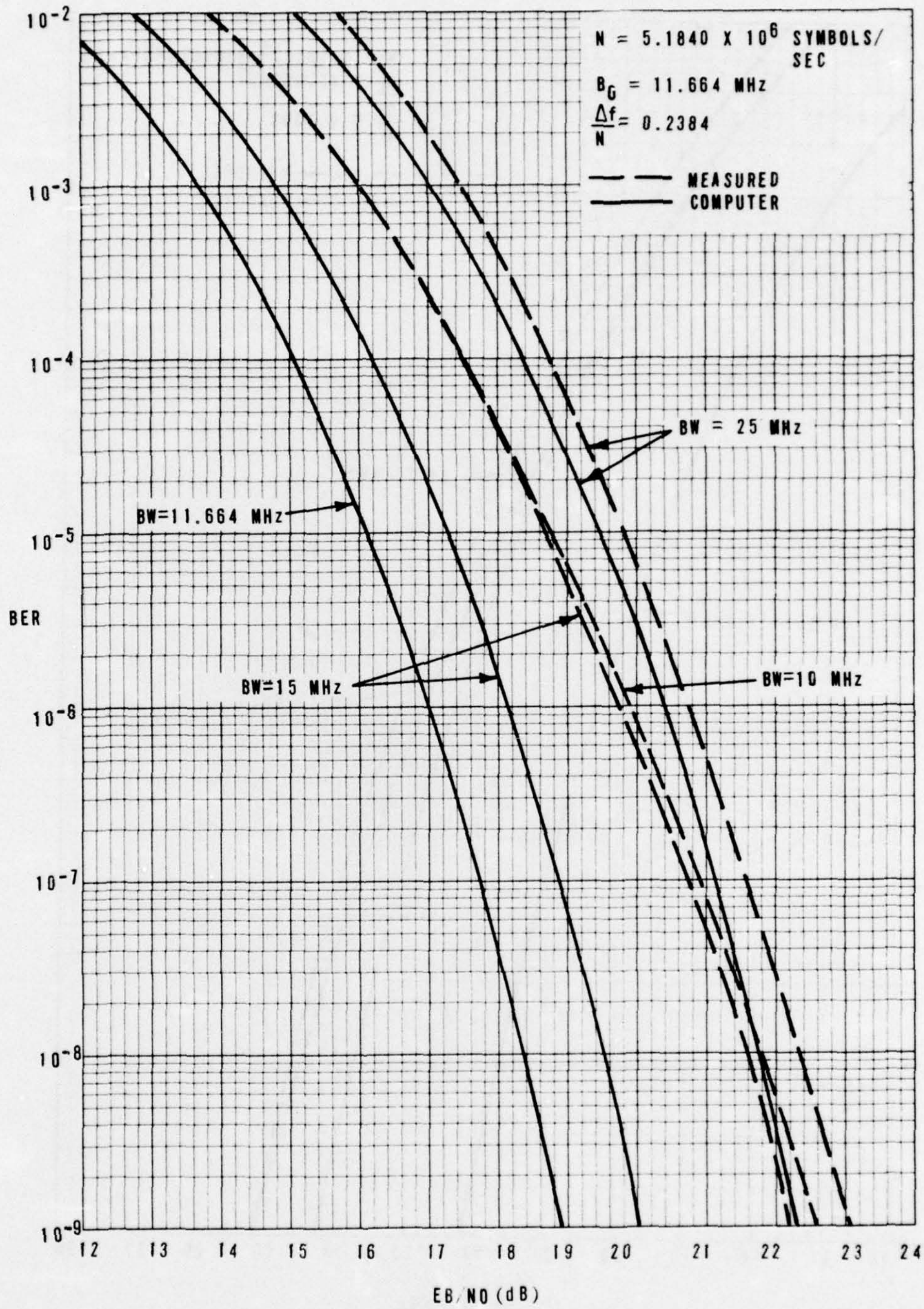
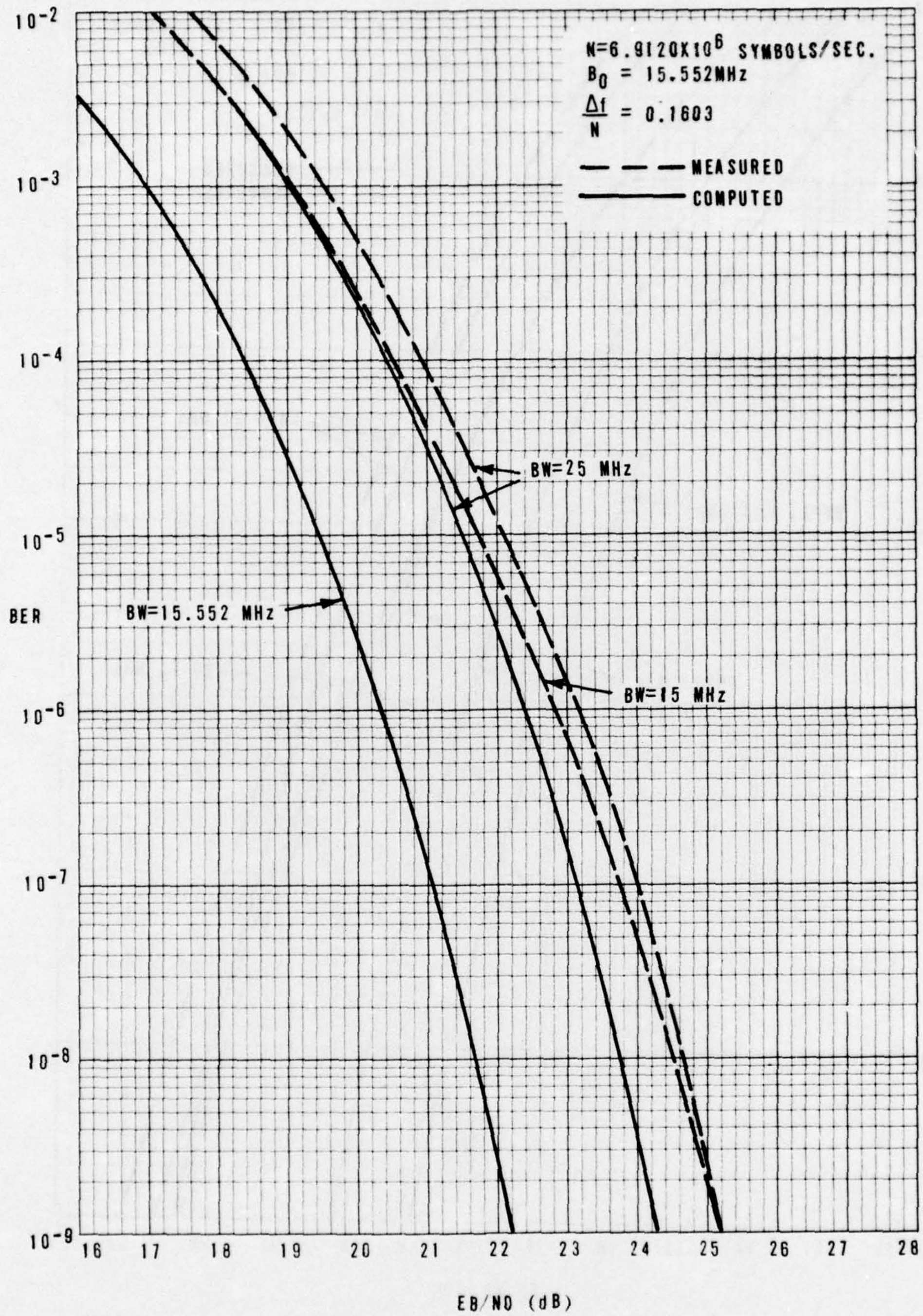


Figure A-5

BIT ERROR RATE VS E_b/N_o (1x12.672 MBPS) - PRFM LEVEL II



The effect of spectral truncation is also apparent in Figure A-6, for error rate performance curve designed BW = 15 MHz. This curve was obtained for dual 9.504 Mbps mission bit streams and, of course, an IF bandwidth of 15 MHz. As indicated in the figure the optimum bandwidth for the above cited total MBS rate and PRFM Level II operation is 23.328 MHz. The error rate performance obtained using a 15 MHz IF bandwidth is approximately 3 dB inferior to that theoretically achieveabel with the optimum bandwidth. With a 25 MHz IF bandwidth, the measured error rate performance is essentially 2 dB worse than the theoretically predicted value. A 2 dB spread between theoretical and predicted performance is not unreasonable all things considered.

Figure A-7 contains the theoretical and measured BER vs. Eb/No curves for the case of a dual 12.672 Mbps mission bit stream input. The theoretical curve is predicted upon the realization of an IF bandwidth of 31.104 MHz. The measured data is based on the use of a narrower than optimum bandwidth, as indicated above, results in the loss or attenuation of spectral components of significant energy content, and consequently degraded error rate performance. A spread of approximately 4 dB between the measured and theoretical performance curves can be noted in Figure A-7. Most of this spread is attributed to the effects of spectral truncation.

A-6 PERFORMANCE LEVEL I DATA

The measured performance level I BER vs. Eb/No data for total MBS rates of 3.168, 6.336, 9.504 and 12.672 MBPS is presented in Figures A-8 through A-11 inclusive. The measured data is presented in dotted lines for easy identification. Also included in the figures are the theoretically predicted performance for the optimum IF bandwidth, and where applicable IF bandwidths of 10, 15 and 25 MHz.

The measured and theoretical error rate performance curves for the case of a single 3.168 MBPS mission bit stream input, PRFM level I and IF bandwidths of 3.888, 7, 10, 15 and 25 MHz are presented in Figure A-8. Referring to the figure it can be noted that the measured performance for a BER of 10^{-9} is approximately 1.4 dB and 1.6 dB worse than the theoretically predicted values for IF bandwidths of 10 MHz and 15 MHz respectively. These performance spreads are considered to be reasonable. For a BER of 10^{-9} and an IF bandwidth of 7 MHz the theoretical vs. measured performance spread is of the order of 2.5 dB. The 2.5 dB performance spread for an IF bandwidth of 7 MHz is not unreasonable large, but is greater than the spread observed for IF bandwidths of 10 and 25

Figure A-6

BIT ERROR RATE VS E_b/N_o (2x9.504 MBPS) - PRFM LEVEL II

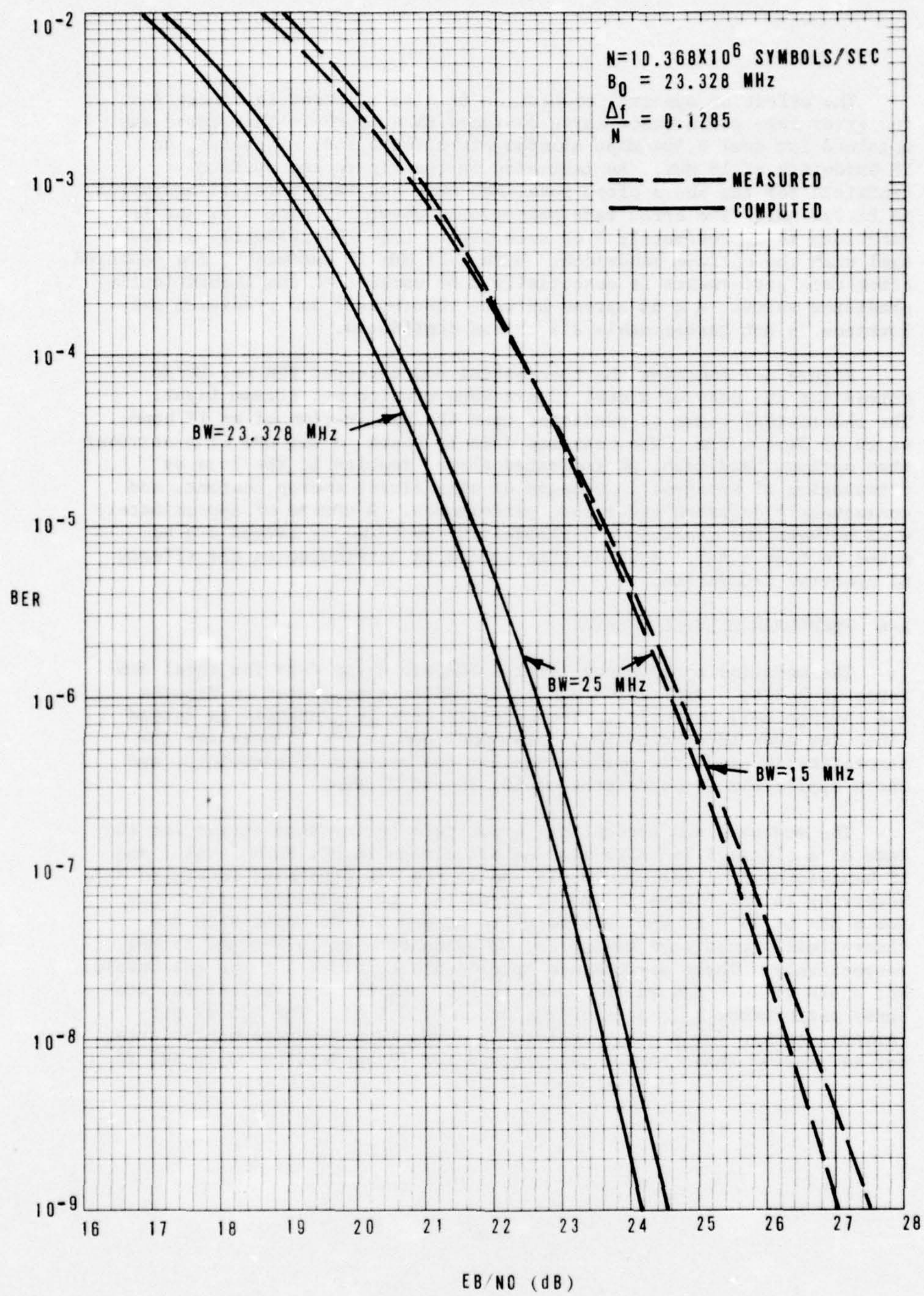


Figure A-7

BIT ERROR RATE VS E_b/N_o (2x12.672 MBPS) - PRFM LEVEL II

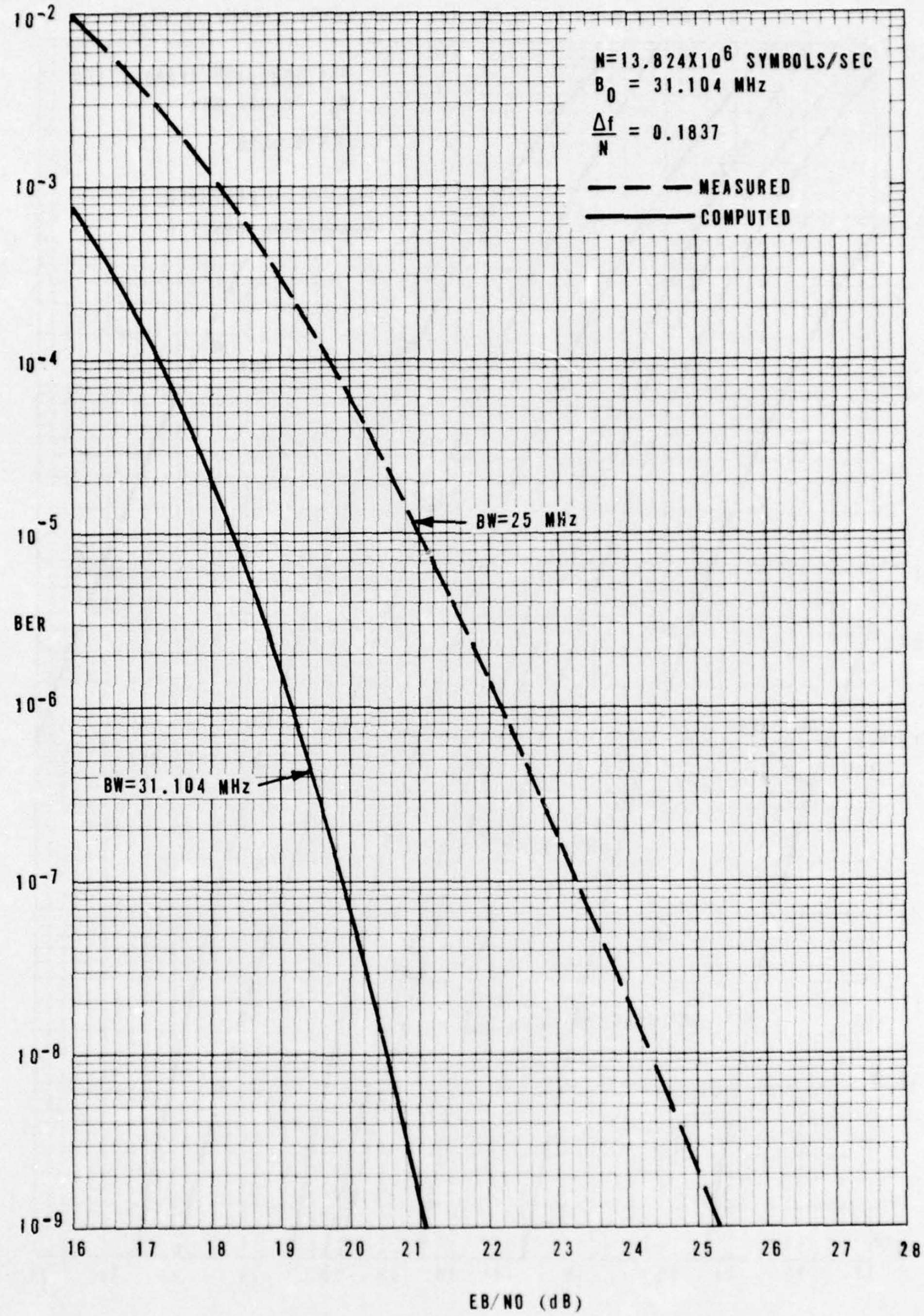
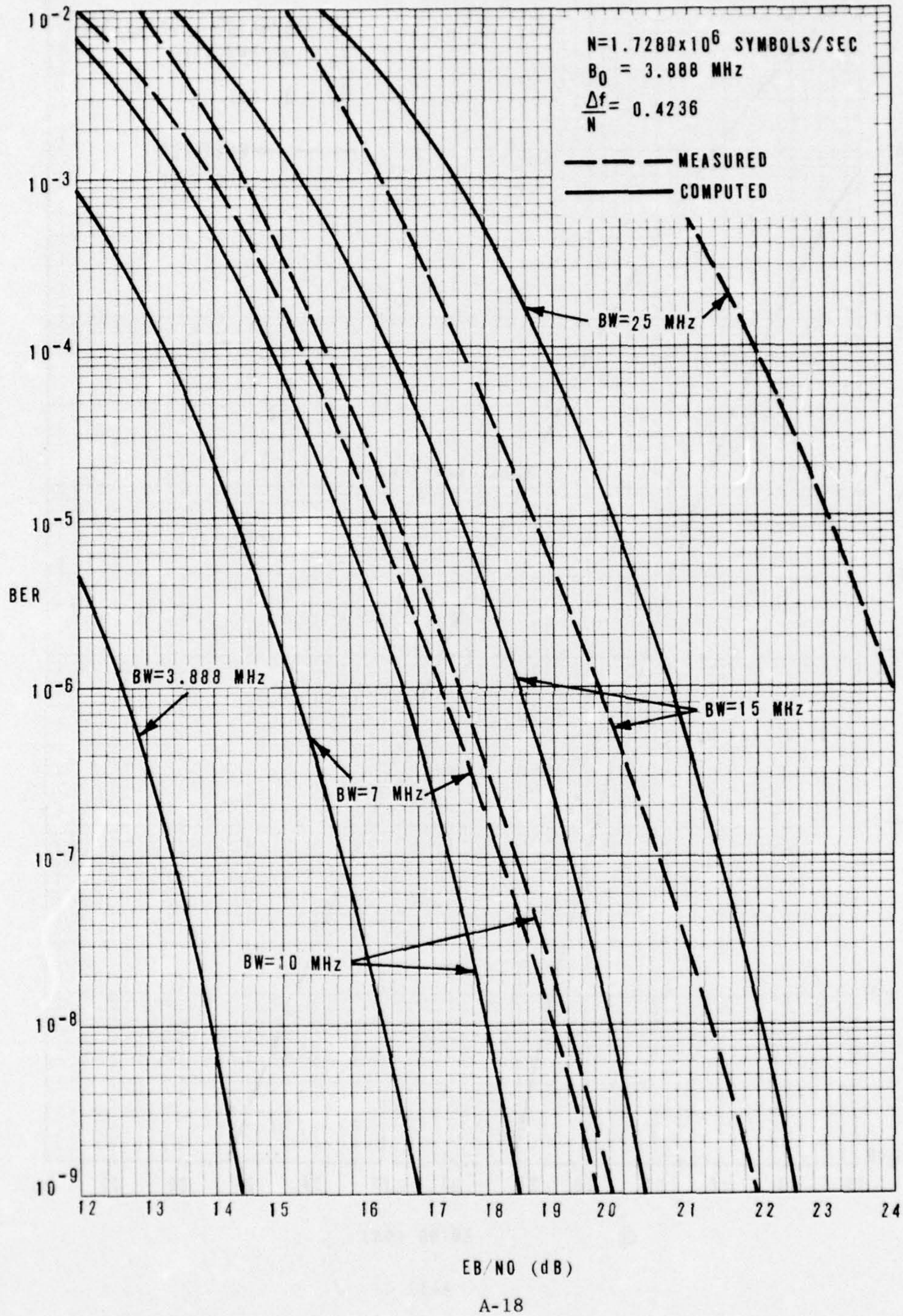


Figure A-8

BIT ERROR RATE VS E_b/N_o (1x3.168 MBPS) - PRFM LEVEL I



MHz. The larger performance spread at an IF bandwidth of 7 MHz is probably due to the less than ideal characteristics of the filter network producing intersymbol distortion.

The theoretical vs. measured performance spread for the 25 MHz IF bandwidth case is approximately 3.9 dB. While this magnitude of performance spread is greater than that observed for the other curves presented in Figure A-8, it is only 0.9 dB worse than that observed for the same bandwidth value, PRFM Level I and a single 12.672 Mbps mission bit stream input (Figure A-11). In the latter case the performance spread was attributed to intersymbol distortion due to the non-linear phase response of the IF filter network. The same explanation can be applied to this particular case with a portion of the performance spread attributable to measurement errors.

Figure A-9 contains the plot of BER vs. Eb/No for the case of a dual 3.168 Mbps mission bit stream and various IF bandwidth values. As can be noted theoretical performance curves for IF bandwidths of 7.776 MHz, 10 MHz, 15 MHz and 25 MHz are presented in the figure. Measured performance curves for IF bandwidths of 15 and 25 MHz are also presented in the figure. Referring to the figure it is noted that the measured performance at a BER of 10^{-9} is approximately 1.6 dB and 2.1 dB worse than the theoretically predicted values for IF bandwidths of 15 MHz and 25 MHz respectively. The above cited theoretical vs. measured performance spread is not considered to be unreasonable. The slope of the measured error rate performance curves suggests the presence of intersymbol distortion, which can be attributed to the non-linear phase characteristics of the IF filter networks.

The PRFM Level I, 1x9.50 MBPS BER vs. Eb/No performance curves are presented in Figure A-10. As indicated in the figure the optimum IF bandwidth was taken to be 11.664 MHz and consequently the use of IF filters of bandwidths equal to 15 MHz and 25 MHz did not result in any spectral truncation effects. As can be noted in the figure at a BER of 10^{-9}, the measured BER performance was approximately 2.2 dB and 1.8 dB worse than the theoretically predicted performance for IF bandwidths of 15 MHz and 25 MHz respectively. The above cited spread between theoretical and measured performance is considered to be of reasonable magnitude. A portion of the performance spread is attributed to intersymbol distortion, the source of which is probably the phase response of the IF filter networks.

Figure A-11 contains the theoretical and measured BER vs. Eb/No curves for the case in which the input is a single 12.672 MBPS mission bit stream and the IF bandwidth takes on values of 15 MHz and 25 MHz.

Figure A-9

BIT ERROR RATE VS E_b/N_o (2x3.168 MBPS) - PRFM LEVEL I

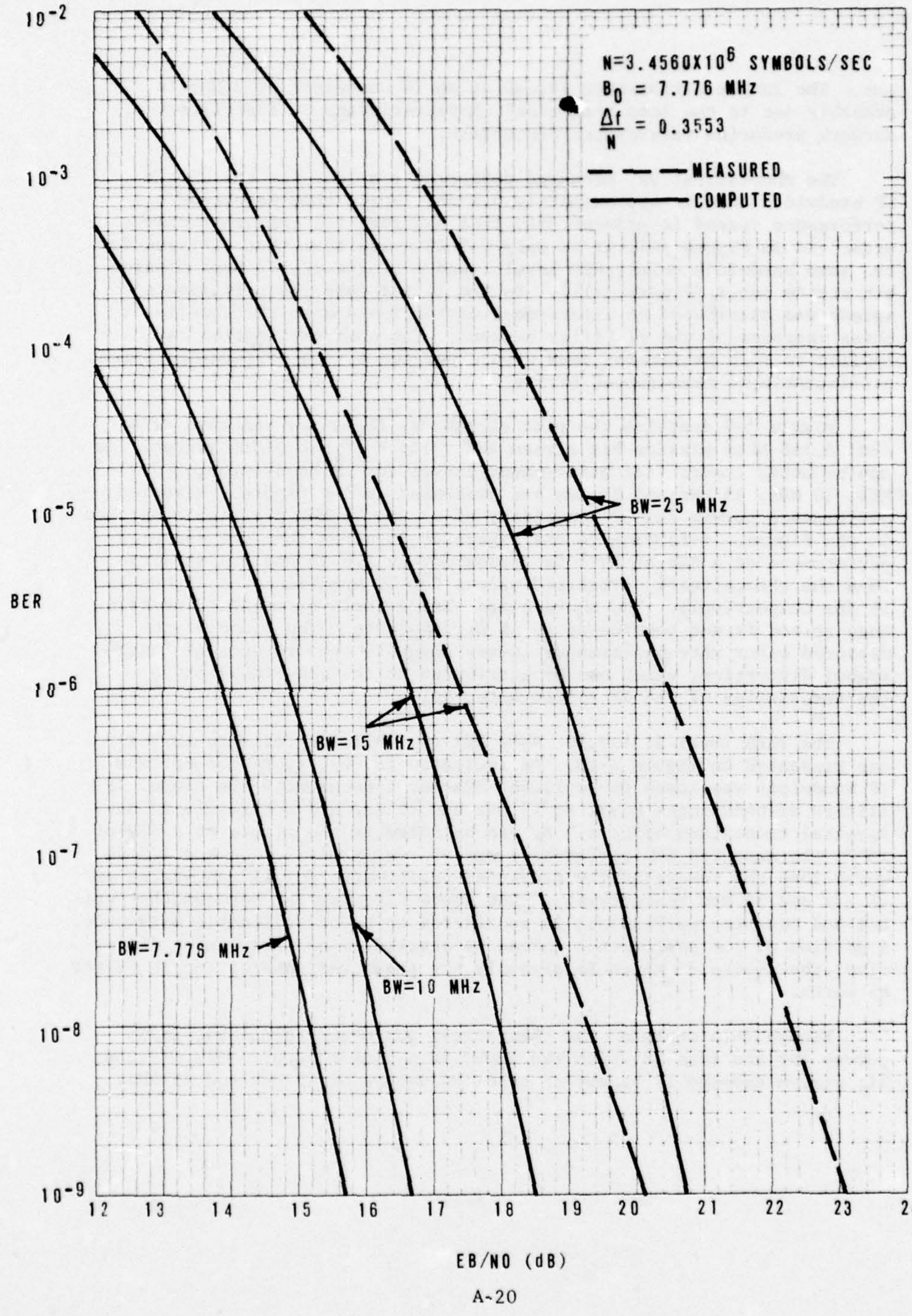


Figure A-10

BIT ERROR RATE VS E_b/N_o (1x9.504 MBPS) - PRFM LEVEL I

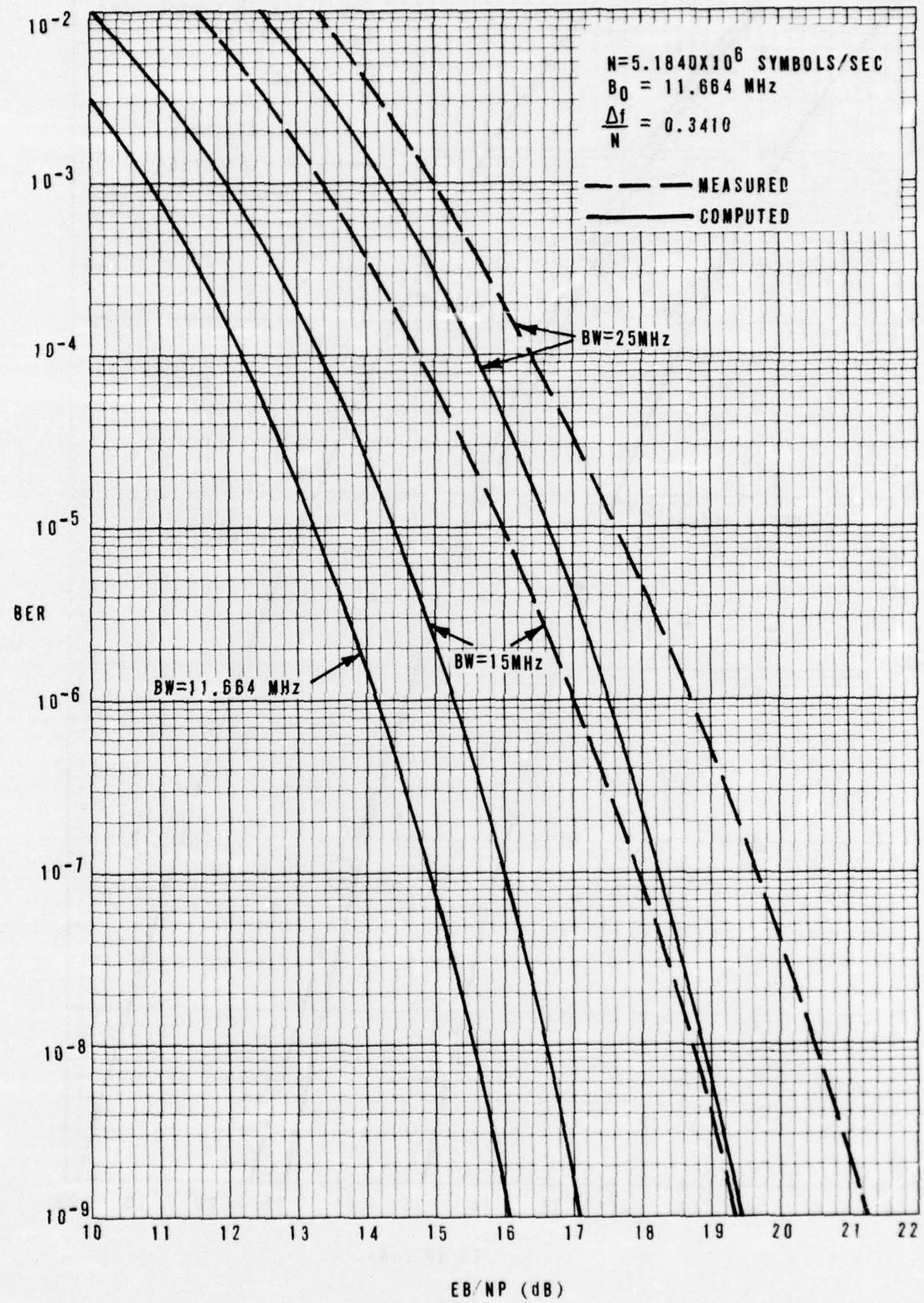
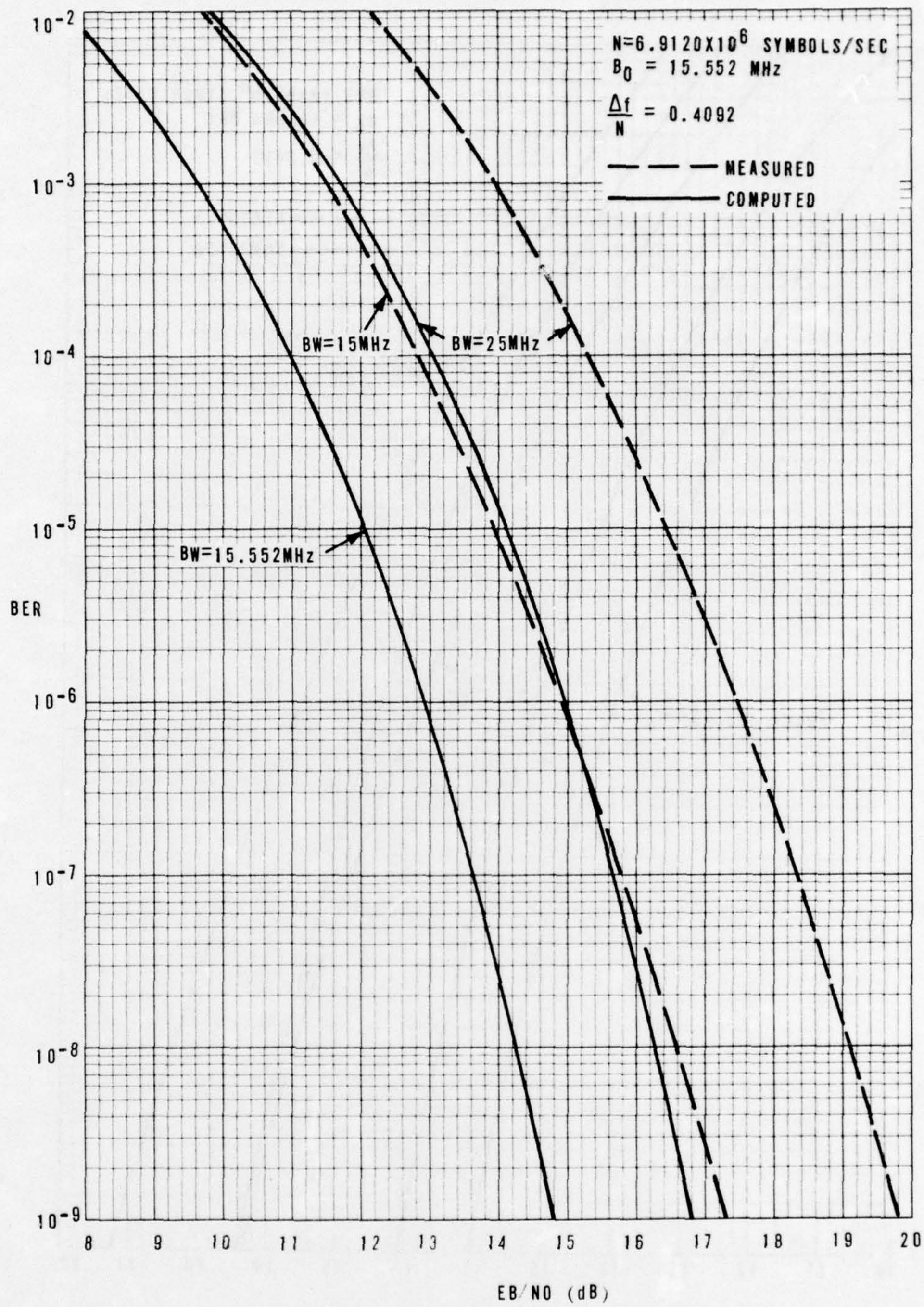


Figure A-11

BIT ERROR RATE VS E_b/N_o (1x12.672 MBPS) - PRFM LEVEL I



As can be noted in the figure that for a BER of 10^{-9}, the measured performance is approximately 2.3 dB and 3.0 dB worse than theoretical for IF bandwidths of 15 MHz and 25 MHz respectively. The slope of the measured error rate performance suggest the presence of intersymbol distortion, which accounts for a portion of the measured vs. theoretical performance spread. The source of the intersymbol distortion is probably the non-linear phase response of the IF filter networks over the band of interest. Since the 15 MHz IF bandwidth is smaller than the indicated optimum value, some spectral truncation is to be expected. However, the effect of spectral truncation does not appear to be as profound for level I performance as it appeared to be for level II performance.

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